NASA CONTRACTOR REPORT

NASA CR-2121

NASA CR-2121

A SIMULATOR EVALUATION OF THE USE OF SPOILERS ON A LIGHT AIRCRAFT

by Carl H. Brainerd and David L. Kohlman

Prepared by
THE UNIVERSITY OF KANSAS, CENTER FOR RESEARCH, INC.
Lawrence, Kansas
for Langley Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1972

1. Report No. NASA CR-2121	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A SIMULATOR EVALUATION OF THE USE OF SPOILERS ON A LIGHT AIRCRAFT		5. Report Date October 1972
		6. Performing Organization Code
7. Author(s) Carl H. Brainerd and David L. Kohlman		8. Performing Organization Report No.
		10. Work Unit No. 760-71-03-01
9. Performing Organization Name and Address The University of Kansas, Center for Research, Inc. Engineering Science Division Lawrence, Kansas		11. Contract or Grant No. NGR 17-002-072
		13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The fixed-base flight simulator at the University of Kansas Flight Research Laboratory was used to evaluate wing spoilers for longitudinal flight path control on a modified Cessna Cardinal aircraft. Spoilers which generated the proper pitching moment to maintain aircraft trim C_L constant could be used as an effective descent rate control. More than 100 simulated ILS approaches were flown by evaluation pilots using both conventional methods and spoiler descent rate control. Three spoiler control schemes were evaluated during the ILS approaches. Using the spoilers for control, instrument approaches could be flown smoothly and precisely with constant airspeed and pitch attitude. While the spoilers could adequately control ILS approaches, a spoiler system with greater authority would be desirable for use in visual approaches.

17. Key Words (Suggested by Author(s)) Flight path control with spoilers; Simulated ILS approaches		18. Distribution Statement Unclassified - Unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 125	22. Price* $3.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

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SUMMARY

The fixed-base flight simulator at the University of Kansas Flight Research Laboratory was used to evaluate wing spoilers for longitudinal flight path control on a modified Cessna Cardinal aircraft. Spoilers which generated the proper pitching moment to maintain aircraft trim C_L constant could be used as an effective descent rate control. Spoilers which did not maintain constant aircraft trim C_L excited the aircraft phugoid mode to a greater degree, so that handling qualities were less satisfactory. More than 100 simulated ILS approaches were flown by evaluation pilots using both conventional methods and spoiler descent rate control. Three spoiler control schemes were evaluated during the ILS approaches. The pilots generally felt that the approaches were easier to fly using the spoilers for control if continuously variable spoiler position was provided by the control scheme. Using the spoilers for control, instrument approaches could be flown smoothly and precisely with constant airspeed and pitch attitude. While the spoilers could adequately control ILS approaches, a spoiler system with greater authority would be desirable for use in visual approaches. The drag of the spoilers had the most influence on aircraft response. Because of this, speedbrakes were predicted to have control and handling characteristics similar to those of constant C_L spoilers.

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LIST OF SYMBOLS

Symbol	Definition	Units
δ	Control surface deflection	deg or rad
δ_{sp}	Deflection of a wing spoiler	deg or rad
δ_{sp_R}	Deflection of right spoiler (0 to 60 deg)	deg or rad
δ_{sp_L}	Deflection of left spoiler (0 to 60 deg)	deg or rad
δ_{lat}	Lateral control input from pilot's control wheel (magnitude variable, ±60 deg max.)	deg or rad
$\delta_{sp_{dlc}}$	Direct lift control spoiler deflection commanded by the pilot (0 to 40 deg)	deg or rad
δ_r	Rudder deflection	deg
mac	Mean aerodynamic chord	ft
g	Unit of acceleration	ft/sec^2
$\bar{x}_{ac_{control}}$	Aerodynamic center location of control lift, fraction of mac	
$\bar{x}_{cg}$	Center of gravity location, fraction of mac	
$\bar{x}_{mp}$	Location of maneuver point, fraction of mac	
α	Angle of attack	rad
$\Delta\alpha$	Change in angle of attack	rad
ATR	Airline Transport Rating	
ASEL	Airplane, Single Engine, Land	
a.c. or ac	Aerodynamic center	
W	Aircraft weight	lb.
U_1	Reference airspeed	ft/sec
q	Pitch rate	rad/sec
u	Forward speed perturbation	ft/sec
β	Sideslip angle	rad
p	Roll rate	rad/sec

LIST OF SYMBOLS, continued

Symbol	Definition	Units
r	Yaw rate	rad/sec
i_H	Horizontal tail incidence angle	rad
ρ	Air density	slug/ft^3
S	Wing area	ft^2
$\bar{c}$	Mean aerodynamic chord	ft
b	Wing span	ft
C_L	Airplane lift coefficient	
C_D	Airplane drag coefficient	
C_m	Airplane pitching moment coefficient	
C_Y	Airplane side force coefficient	
C_ℓ	Airplane rolling moment coefficient	
C_n	Airplane yawing moment coefficient	
C_{T_y}	Propellor side force coefficient	
C_{T_n}	Propellor yawing moment coefficient	
I_{xx}	Airplane roll inertia	slug-ft^2
I_{yy}	Airplane pitch inertia	slug-ft^2
I_{zz}	Airplane yaw inertia	slug-ft^2
m	Airplane mass	slugs
$\bar{q}$	Dynamic pressure	lb/ft^2

Longitudinal Dimensional Stability Derivatives

$$Z_{\alpha} = -\frac{\bar{q}\, S\, (C_{L_{\alpha}} + C_{D_1})}{m}$$

$$M_{\alpha} = \frac{\bar{q}\, S\, \bar{c}\, C_{m_{\alpha}}}{I_{yy}}$$

$$X_{\alpha} = -\frac{\bar{q}\, S\, (C_{D_{\alpha}} - C_{L_1})}{m}$$

$$Z_{\dot{\alpha}} = -\frac{\bar{q}\, S\, \bar{c}\, C_{L_{\dot{\alpha}}}}{2\, m\, U_1}$$

$$M_{\dot{\alpha}} = \frac{\bar{q}\, S\, \bar{c}^2\, C_{m_{\dot{\alpha}}}}{2 I_{yy} U_1}$$

$$Z_{i_H} = -\frac{\bar{q}\, S\, C_{L_{i_H}}}{m}$$

$$X_{i_H} = -\frac{\bar{q}\, S\, C_{D_{i_H}}}{m}$$

$$M_{i_H} = \frac{\bar{q}\, S\, \bar{c}\, C_{m_{i_H}}}{I_{yy}}$$

$$Z_{q} = -\frac{\bar{q}\, S\, \bar{c}\, C_{L_q}}{2\, m\, U_1}$$

$$M_{q} = \frac{\bar{q}\, S\, \bar{c}^2\, C_{m_q}}{2\, I_{yy} U_1}$$

$$Z_{u} = -\frac{\bar{q}\, S\, (C_{L_u} + 2 C_{L_1})}{m\, U_1}$$

$$X_{u} = -\frac{\bar{q}\, S\, (C_{D_u} + 2\, C_{D_1})}{m\, U_1}$$

$$M_{u} = \frac{\bar{q}\, S\, \bar{c}\, (C_{m_u} + 2\, C_{m_1})}{I_{yy}\, U_1}$$

$$Z_{\delta_{sp}} = -\frac{\bar{q}\, S\, C_{L_{\delta_{sp}}}}{m}$$

$$X_{\delta_{sp}} = -\frac{\bar{q}\, S\, C_{D_{\delta_{sp}}}}{m}$$

$$M_{\delta_{sp}} = \frac{\bar{q}\, S\, \bar{c}\, C_{m_{\delta_{sp}}}}{I_{yy}}$$

Lateral-Directional Dimensional Stability Derivatives

$$Y_\beta = \frac{\bar{q}\,S\,(C_{y_\beta} + C_{T_{y_\beta}})}{m}$$

$$L_\beta = \frac{\bar{q}\,S\,b\,C_{\ell_\beta}}{I_{xx}}$$

$$N_\beta = \frac{\bar{q}\,S\,b\,(C_{n_\beta} + C_{T_{n_\beta}})}{I_{zz}}$$

$$Y_p = \frac{\bar{q}\,S\,b\,C_{y_p}}{2\,m\,U_1}$$

$$L_p = \frac{\bar{q}\,S\,b^2\,C_{\ell_p}}{2\,I_{xx}\,U_1}$$

$$N_p = \frac{\bar{q}\,S\,b^2\,C_{n_p}}{2\,I_{zz}\,U_1}$$

$$Y_r = \frac{\bar{q}\,S\,b\,C_{y_r}}{2\,m\,U_1}$$

$$L_r = \frac{\bar{q}\,S\,b^2\,C_{\ell_r}}{2\,I_{xx}\,U_1}$$

$$N_r = \frac{\bar{q}\,S\,b^2\,C_{n_r}}{2\,I_{zz}\,U_1}$$

$$Y_{\delta_r} = \frac{\bar{q}\,S\,C_{y_{\delta_r}}}{m}$$

$$L_{\delta_r} = \frac{\bar{q}\,S\,b\,C_{\ell_{\delta_r}}}{I_{xx}}$$

$$N_{\delta_r} = \frac{\bar{q}\,S\,b\,C_{n_{\delta_r}}}{I_{zz}}$$

$$Y_{\delta_{sp}} = \frac{\bar{q}\,S\,C_{y_{\delta_{sp}}}}{m}$$

$$L_{\delta_{sp}} = \frac{\bar{q}\,S\,b\,C_{\ell_{\delta_{sp}}}}{I_{xx}}$$

Longitudinal Nondimensional Stability Derivatives

$$C_{D_u} = \frac{\partial C_D}{\partial(\frac{u}{U_1})}$$

$$C_{L_u} = \frac{\partial C_L}{\partial(\frac{u}{U_1})}$$

$$C_{m_u} = \frac{\partial C_m}{\partial(\frac{u}{U_1})}$$

$$C_{D_\alpha} = \frac{\partial C_D}{\partial \alpha}$$

$$C_{L_\alpha} = \frac{\partial C_L}{\partial \alpha}$$

$$C_{m_\alpha} = \frac{\partial C_m}{\partial \alpha}$$

$$C_{L_{\dot{\alpha}}} = \frac{\partial C_L}{\partial(\frac{\dot{\alpha}\bar{c}}{2U_1})}$$

$$C_{m_{\dot{\alpha}}} = \frac{\partial C_m}{\partial(\frac{\dot{\alpha} c}{2U_1})}$$

$$C_{L_q} = \frac{\partial C_L}{\partial(\frac{q\bar{c}}{2U_1})}$$

$$C_{m_q} = \frac{\partial C_m}{\partial(\frac{q\bar{c}}{2U_1})}$$

$$C_{D_{i_H}} = \frac{\partial C_D}{\partial i_H}$$

$$C_{L_{i_H}} = \frac{\partial C_L}{\partial i_H}$$

$$C_{m_{i_H}} = \frac{\partial C_m}{\partial i_H}$$

$$C_{D_{\delta_{sp}}} = \frac{\partial C_D}{\partial \delta_{sp}}$$

$$C_{L_{\delta_{sp}}} = \frac{\partial C_L}{\partial \delta_{sp}}$$

$$C_{m_{\delta_{sp}}} = \frac{\partial C_m}{\partial \delta_{sp}}$$

Lateral-Directional Nondimensional Stability Derivatives

$C_{y_\beta} = \dfrac{\partial C_y}{\partial \beta}$

$C_{\ell_\beta} = \dfrac{\partial C_\ell}{\partial \beta}$

$C_{n_\beta} = \dfrac{\partial C_n}{\partial \beta}$

$C_{T_{y_\beta}} = \dfrac{\partial C_{T_y}}{\partial \beta}$

$C_{T_{n_\beta}} = \dfrac{\partial C_{T_n}}{\partial \beta}$

$C_{y_p} = \dfrac{\partial C_y}{\partial (\frac{pb}{2U_1})}$

$C_{\ell_p} = \dfrac{\partial C_\ell}{\partial (\frac{pb}{2U_1})}$

$C_{n_p} = \dfrac{\partial C_n}{\partial (\frac{pb}{2U_1})}$

$C_{y_r} = \dfrac{\partial C_y}{\partial (\frac{rb}{2U_1})}$

$C_{\ell_r} = \dfrac{\partial C_\ell}{\partial (\frac{rb}{2U_1})}$

$C_{n_r} = \dfrac{\partial C_n}{\partial (\frac{rb}{2U_1})}$

$C_{y_{\delta_r}} = \dfrac{\partial C_y}{\partial \delta_r}$

$C_{\ell_{\delta_r}} = \dfrac{\partial C_\ell}{\partial \delta_r}$

$C_{n_{\delta_r}} = \dfrac{\partial C_n}{\partial \delta_r}$

$C_{y_{\delta_{sp}}} = \dfrac{\partial C_y}{\partial \delta_{sp}}$

$C_{\ell_{\delta_{sp}}} = \dfrac{\partial C_\ell}{\partial \delta_{sp}}$

$C_{n_{\delta_{sp}}} = \dfrac{\partial C_n}{\partial \delta_{sp}}$

1. INTRODUCTION

As aircraft have become larger in recent years their moments of inertia have increased more than aerodynamic moments. This has caused pitch response to become more sluggish as airplane size increased, which has made flight path control in the landing approach much more difficult. To solve this problem, the concept of Direct Lift Control (DLC) evolved. A DLC control system allows some degree of lift control independent of an aircraft's pitch response by utilizing spoilers, maneuvering flaps, symmetrically deflected ailerons, etc. to generate lift increments. Reference 1 contains a short history of DLC work in this country. The DLC concept has been evaluated experimentally on a number of large jet aircraft and Navy carrier-based aircraft, both in simulators and on full-scale vehicles. The use of DLC in each case reduced the pilot workload during the landing approach because of the easier and more precise flight path control which resulted. Reference 1 also reports that the first commercial application of DLC may be on the McDonnell-Douglas DC-10 and Lockheed L-1011. So the usefulness of Direct Lift Control on large, heavy aircraft is well established.

However, little work has been done relating DLC to light aircraft applications. References 2 - 5 indicate that in recent years approximately 50 % of general aviation accidents occured in the landing phase, and that more than half of the landing accidents were the result of overshoots or undershoots. Thus, more than one fourth of all general aviation accidents (1000 or more per year) are the result of the inability to properly control flight path in the landing approach. It appears that there is some need in light air-

craft, too, for an advanced method of flight path control such as DLC.

This thesis describes a flight simulator evaluation of spoilers as the primary longitudinal control on a light aircraft in the landing approach. The work was done at the Flight Research Laboratory, University of Kansas, in connection with NASA Grant NGR 17-002-072, "An Investigation of Improved Control Methods for Light and General Aviation Aircraft." The work being done under this Grant includes the following:

1. Design, build, and flight test a new wing for a light airplane (Cessna Cardinal) with the objective of improving cruise performance.
2. Develop a high lift system for the new wing to insure that takeoff and landing performance is not impaired.
3. Incorporate a roll control system using spoilers instead of ailerons.
4. Develop a direct lift control system to improve flight path control in the landing approach.
5. Design and build a flight simulator for use in evaluating the handling characteristics of the modified airplane.

Reference 6 contains the aerodynamic analysis and preliminary design of the new wing with lateral and longitudinal spoiler controls. That analysis is analytic, not experimental. Reference 7 describes the design and development of the flight simulator. This thesis relates to References 6 and 7 in that it describes how the simulator

was used to evaluate the handling qualities of the new wing design, particularly the direct lift control system.

The new wing has been designed by the University of Kansas Flight Research Laboratory and is being manufactured by Robertson Aircraft Corporation, Bellevue, Washington. The first flight of the modified airplane is expected in March, 1972. The wing features include single-slotted Fowler flaps, full span leading edge Kruger flaps, and spoilers on the top of each wing. The spoiler on each side is actually two spoiler panels connected together to act as one. The spoilers are to be used for both lateral control (replacing ailerons) and longitudinal control. The spoilers on each side deflect symmetrically for lift control and differentially for roll control. To accomplish this, the spoilers are actuated by a mechanical mixer which combines the lateral and longitudinal control inputs.

The purpose of this investigation was to use the flight simulator to evaluate the modified Cardinal longitudinal spoiler control system from the pilot's point of view. The specific objectives were:

1. Investigate the general suitability of spoilers for longitudinal flight path control. Compare with conventional throttle-elevator control for effectiveness and smoothness.
2. Determine the spoiler pitching moment characteristics which result in good control and handling qualities, and whether a spoiler-elevator interconnect will be needed on the modified Cardinal.
3. Using several different pilots, evaluate spoilers as a

flight path control for Instrument Landing System (ILS) approaches. Determine whether the spoiler control results in improved pilot performance of the glide slope tracking task, or if the task is made easier with the same level of performance.

4. Investigate several spoiler control schemes and the corresponding cockpit spoiler controllers for pilot preference. Recommend a spoiler controller for initial installation in the modified Cardinal aircraft.

2. TEST SETUP

2.1 Flight Simulator

The modified Cardinal spoiler system was "flown" on the general purpose fixed-base flight simulator at the Flight Research Laboratory (Reference 7). The basic elements of the simulator are outlined below.

2.1.1 Cockpit

The simulator cabin is the center fuselage section of a Beechcraft Duke. The flight instruments were removed and replaced with electrically driven instruments. A loudspeaker behind the instrument panel provides simulated engine noise which changes in pitch and volume in a realistic manner. The cabin interior remained stock, and thus realistic. The instrument panel, shown in Figure 1, is arranged in the so-called "T" configuration which has become more or less standard in new aircraft. The ILS indicator is in the lower right corner of the panel. The other instruments on the bottom row, angle of attack and "g" meters, are not normally found in light aircraft. Power control is via a center pedestal-mounted power lever with a bicycle-type handgrip. On the center panel above the throttle are the tachometer and spoiler deflection indicator. In front of the pilot's windshield is the television monitor used with the visual display system. The TV, of course, was turned off for ILS approaches.

2.1.2 Computers

The simulator is controlled by EAI 580 and TR-48 general purpose

analog computers. The computers were programmed to solve the six degree-of-freedom, non-linear, small perturbation airplane equations of motion as given in Reference 8. The programming is detailed in Reference 7. Since small perturbation equations were used, only one flight condition could be simulated without reprogramming. The calculation of aircraft position with respect to an earth-fixed axis system allowed navigation-type problems such as the ILS to be simulated. Two programming additions were made specifically for this investigation:

1. <u>Turbulence</u> In an attempt to make the ILS approach task more realistic, a turbulence generator was wired up to feed angle of attack disturbances representing sharp-edged vertical gusts to the equations of motion. R.M.S. gust velocity was 2 ft/sec and peak gust velocity was 4.8 ft/sec. This turbulence was not patterned after any specific model, but was determined by what could be done with the very limited computer equipment available. The pilots' subjective opinion was that the simulator instrument readings in turbulence were similar to those they had observed in flight through real turbulence. The analog programming diagram is shown in Figure 2. Pulses from decade counter 0 cause up-counter 0 to steadily count up from 0 to 15 (in binary) and reset. Thus, the outputs of flip-flops 0 - 3 in the counter are constantly changing at different frequencies. The four AND gates combine the flip-flop outputs in various combinations to get plus and minus angle of attack pulses. The plus and minus pulses are

chopped up at different frequencies by the two decade counters. To the pilot, this turbulence looks like random short period pitching motion with continuous phugoid excitation. The aircraft response to this turbulence can be seen in Figure 3.

2. Instrument Landing System To evaluate spoilers as an aid in making instrument approaches, an ILS was set up on the computer. Reader familiarity with ILS is assumed here. If needed, Reference 9 has a good description of the system. On the simulated ILS, the glideslope needle indicated $\pm$ 0.5 deg. deviation and the localizer needle indicated $\pm$ 2.5 deg. The ILS analog circuits are shown in Figure 4. The on-course Z (altitude) and Y (lateral position) are linear functions of X (forward distance, toward runway). The deviation needles display linear Z and Y error multiplied by a gain term which is inversely proportional to distance from the station so that- (gain) X (distance) = constant. Since the required gain gets very large at small ranges, the gain of this simulated system remains constant at ranges less than about 1000 feet. This corresponds to an altitude of about 52 feet on a 3 degree glideslope. Since ILS guidance is normally terminated not lower than 100 feet, the usefulness of the simulation is not degraded. Figure 5 shows the overall approach situation in plan and side views.

2.1.3 Spoiler Controllers

Three methods of controlling symmetrical spoiler deflection (DLC) from the cockpit were set up for evaluation, as follows:

1. Bang-Bang Position Control A standard aircraft pitch trim

switch (2-way, center off, spring-loaded) was installed in the top of the throttle handle, to be actuated by the thumb. Then, with the spoilers positioned at 50% travel (with a separate on-off switch), pushing the trim switch forward commanded 0 deflection, and pushing the switch rearward commanded 100% deflection. Thus, the sense of the spoiler control was the same as the throttle on which it was mounted. Forward was for airplane "up" and back was for "down." In short, the spoilers could be popped either up or down from a bias position to change the flight path in the desired direction. A first order lag with a time constant of 1 second simulated the dynamics of a servo-actuator. When the switch was released, 50% deflection was again commanded. It should be noted that to maintain 0 or 100% deflection, constant pressure had to be held against the spring in the switch. Figure 6 shows this controller installation in the cockpit.

2. Thumbwheel Position Command A small wheel similar to a miniature pitch trim wheel was mounted on the left side of the throttle handle. As the pilot's hand held the throttle, his thumb rested naturally on the wheel. Rotation of the thumbwheel commanded any spoiler position from 0 to 100% proportional to the wheel's angular position. The full range of deflections was covered by approximately 270 deg. of wheel rotation (the wheel was connected to a miniature one-turn potentiometer inside the throttle handle). As with

controller (1) above, a first order lag simulated servo response to position command. Since this controller was, in effect, a sort of longitudinal trim control using spoilers, the sense of the control was made the same as for a conventional elevator trim wheel when used for flight path control. That is, rotating the wheel forward called for more spoiler deflection (airplane down), and rotation aft gave less deflection (airplane up). This was intended to minimize pilot confusion about which way to move the control to get a desired airplane response. This controller is shown in Figure 7.

Note that the sense of this control was opposite to that of the bang-bang position controller. The bang-bang switch was tried experimentally with both possible senses, but neither seemed natural enough for the pilots to use without consciously thinking about which way to move the switch. The use and sense of the thumbwheel were as natural as possible for several reasons:

(a) A forward rotation of the wheel commanded a forward rotation of the spoilers (increased deflection).

(b) A nose-down rotation of the wheel achieved the same glide path response as a nose-down rotation of the airplane or a nose-down trim change.

(c) An upward motion of the thumb on the back of the wheel commanded an airplane response which would also tend to move the ILS glide slope needle upward.

3. <u>Bang-Bang Rate Control</u> This controller utilized the thumbswitch described in (1), but instead of commanding spoiler position, the switch commanded a deflection rate. This simulated spoilers driven by a constant speed electric motor, with the switch merely turning the motor on and off. This controller was analogous to conventional electric pitch trim; pushing forward on the switch caused the spoilers to run up (airplane down), and pushing rearward ran the spoilers down. When the switch was released, the spoilers stopped where they were at that point. The deflection rate was about 10 degrees per second, which was thought to be representative of the spoiler actuator on the new wing, a standard Cessna electric flap motor.

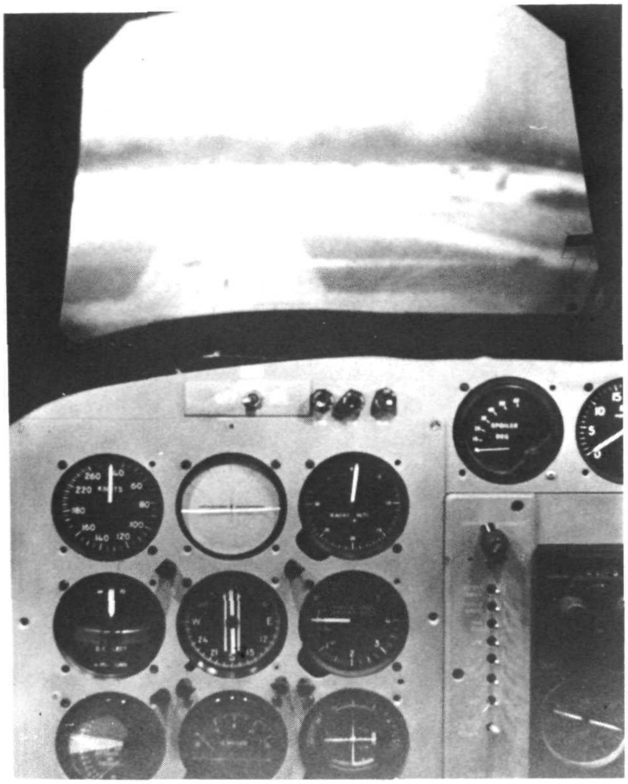


Figure 1

Simulator Instrument Panel

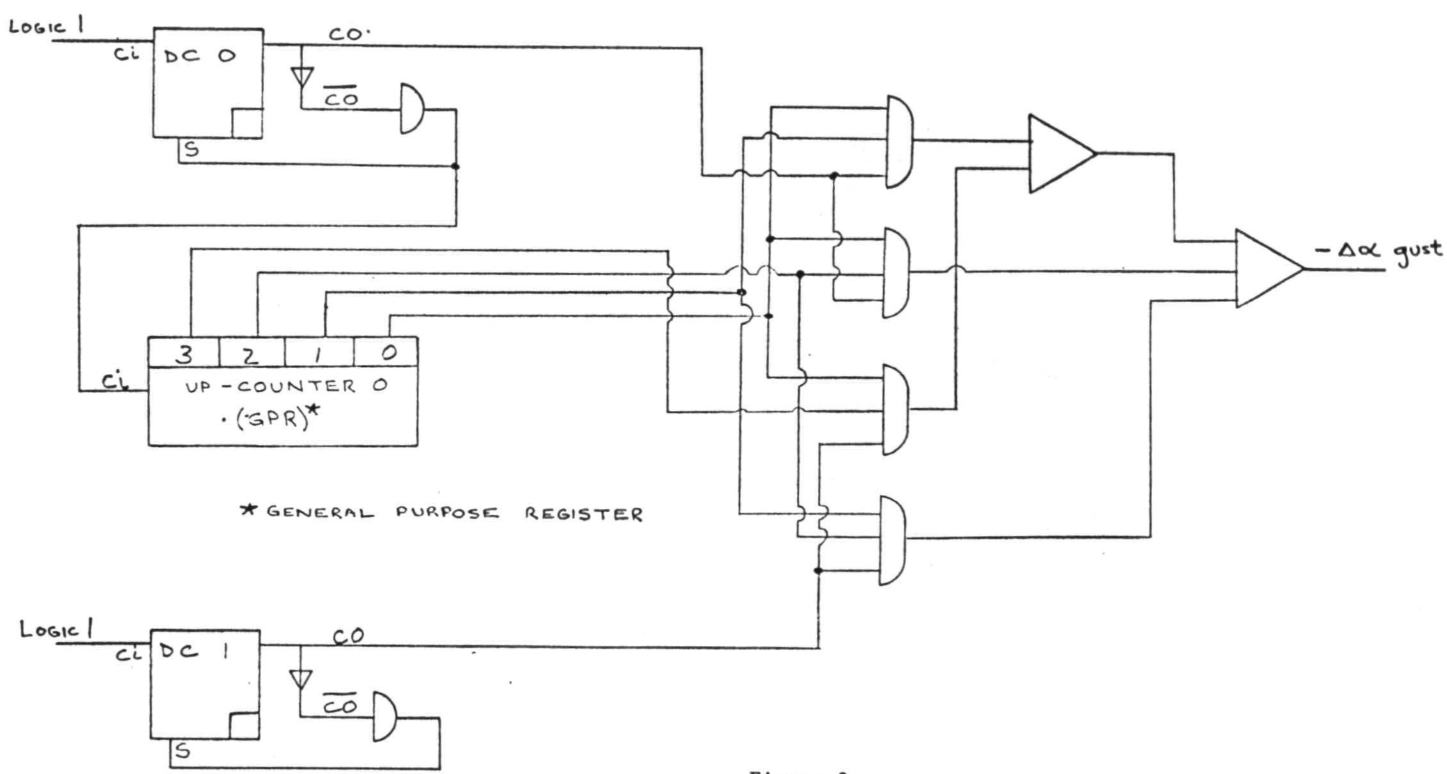


Figure 2

Turbulence Generator Circuit

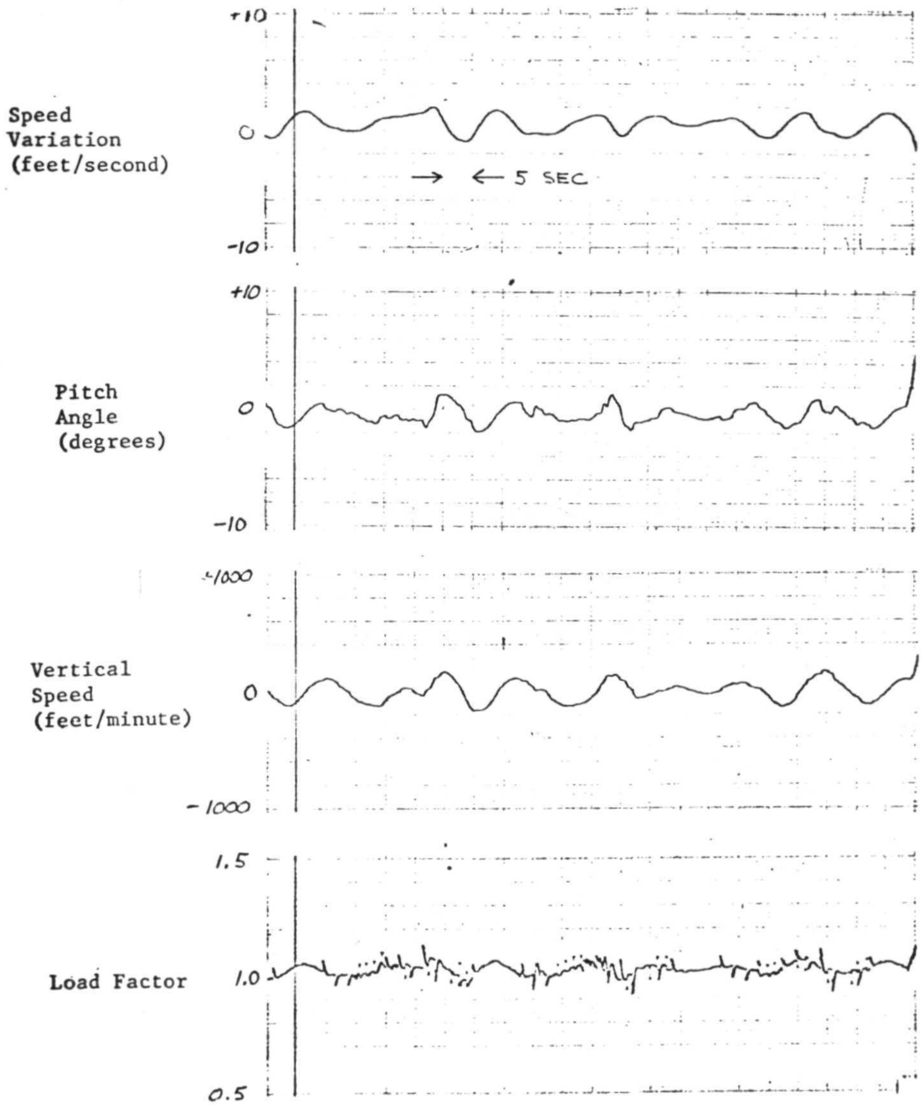


Figure 3

Aircraft Response to Turbulence

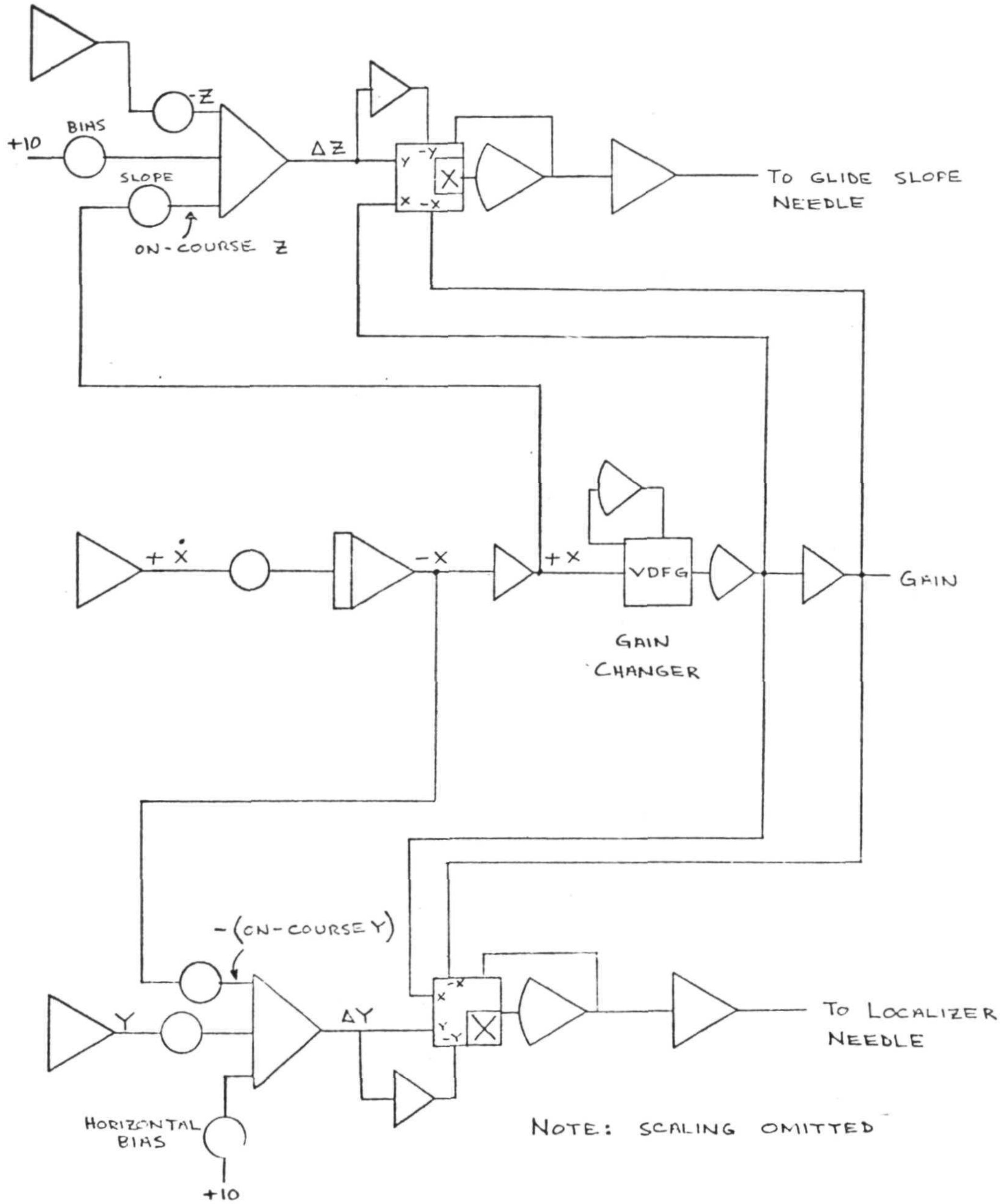


Figure 4

Instrument Landing System Analog Computer Circuit

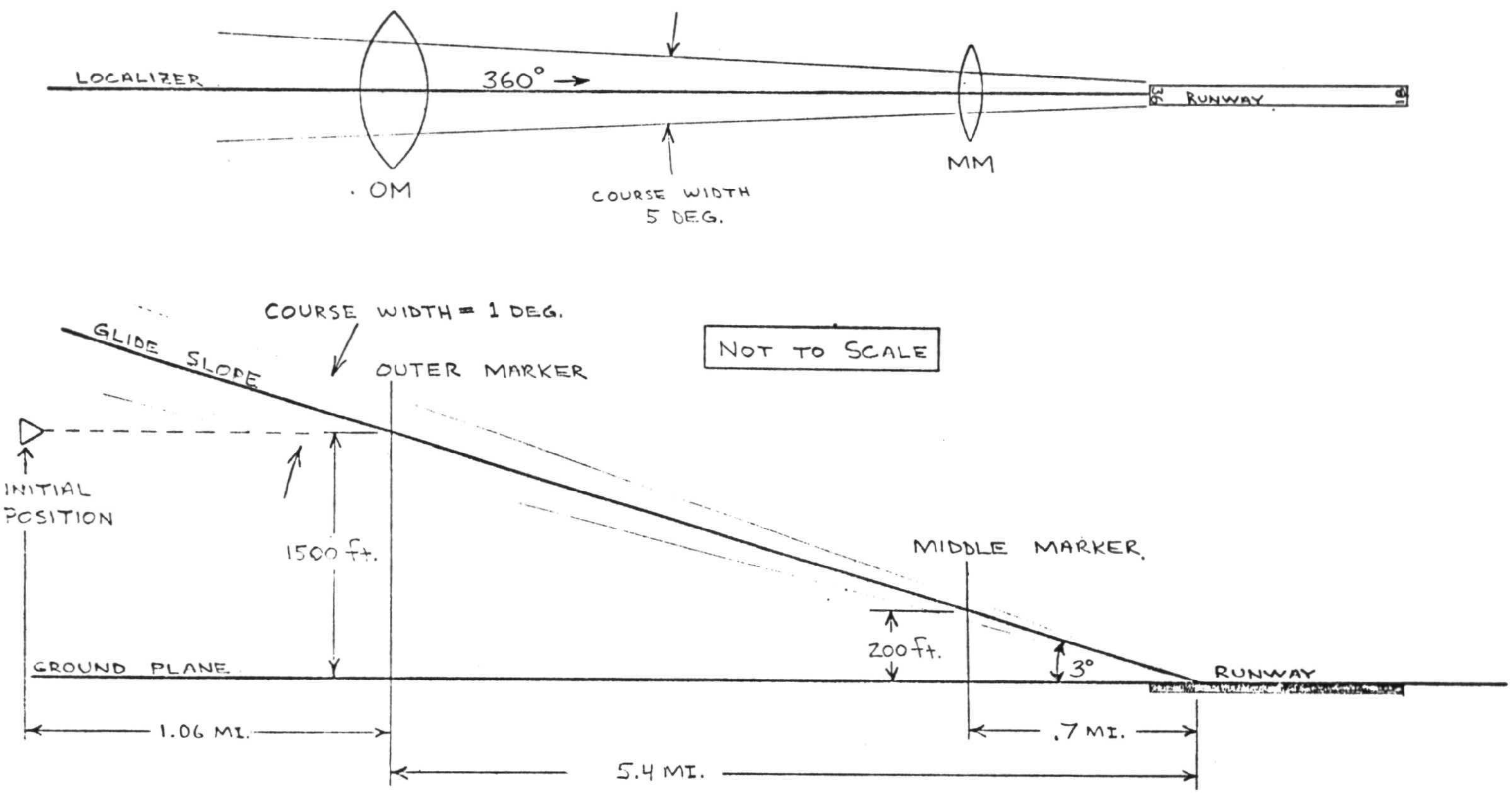


Figure 5

Instrument Landing System Arrangement

Figure 6

Spoiler Thumbswitch Installation

Figure 7

Spoiler Thumbwheel Installation

2.2 Evaluation Airplane

The airplane which was simulated in this investigation was a Cessna Cardinal with new wings designed by the Flight Research Laboratory. A detailed analysis of this design may be found in Reference 6. Figure 8 shows the general arrangement of the modified aircraft. Important features of the design are:

1. Reduced wing area (110 ft^2) compared with the production Cardinal (175 ft^2)
2. High lift system employing leading and trailing edge flaps
3. Spoilers which are used for both roll control and direct lift control

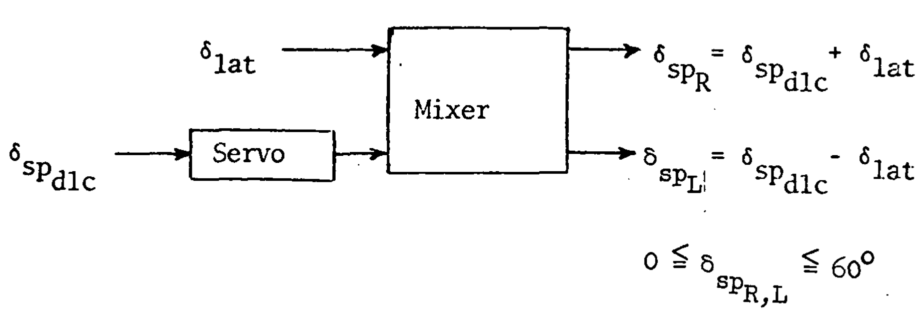
The deflection of each spoiler is determined by a mechanical mixer as follows:

Let δ_{sp_R} = deflection of right spoiler (0 to 60 deg.)

δ_{sp_L} = deflection of left spoiler (0 to 60 deg.)

δ_{lat} = lateral control input from pilot's control wheel (magnitude variable, ± 60 deg.max)

$\delta_{sp_{dlc}}$ = direct lift spoiler deflection commanded by the pilot (0 to 40 deg.)



Right and left spoiler deflections are limited mechanically by the mixer to the range between 0 and 60 degrees. When the computed deflection of either spoiler exceeds a limit, the deflection remains constant at that limit. For example, if $\delta_{sp_{dlc}} = 0$, a roll command will cause one spoiler to deflect upward, while the other spoiler will not move. Negative spoiler deflections are, of course, not possible. However, if $\delta_{sp_{dlc}} = 20$ degrees, both spoilers will be deflected 20 degrees initially. Now a roll command will cause both spoilers to move, one up and one down. Thus, twice as much rolling moment is generated by a given wheel deflection when $\delta_{sp_{dlc}} > 0$ (compared to $\delta_{sp_{dlc}} = 0$, and assuming the spoiler limits are not reached). Therefore, lateral control has some non-linear characteristics which were included in the simulation.

The estimated dimensional stability derivatives of the modified Cardinal are listed in Table 1. These derivatives come from either Reference 6 or the stability and control review done by the writer and Mr. Will Bolton in the summer of 1971. The flight condition chosen for the evaluation flights was-

Landing configuration (full flaps)

Weight = 2500 lb. (maximum gross weight)

Altitude = sea level, standard day

Airspeed = 107 fps = 73 mph = 63.5 kt CAS (1.2 X stall speed)

Center of gravity @ 3.3 % mac

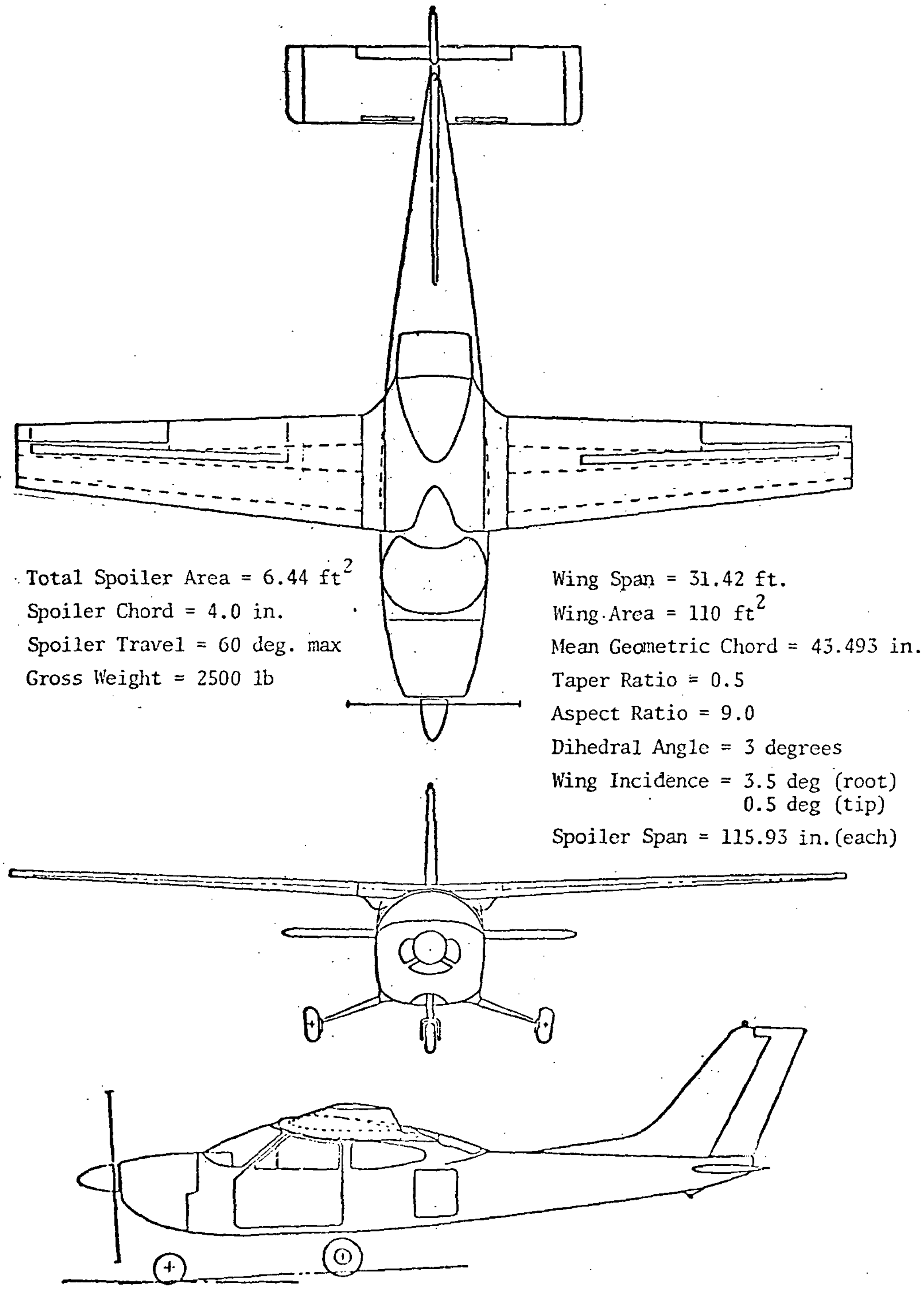


Figure 8

Modified Cardinal General Arrangement

TABLE 1

Modified Cardinal Dimensional Stability Derivatives

Landing configuration, full flaps
Sea level, standard day
c.g. at 3.3 % mac
U_1 = 107 fps = 73 mph = 63.5 kt CAS
Weight = 2500 lb.
Derivatives are per radian.

Z_α	= -144.5	Y_β	= -10.78
M_α	= -13.65	L_β	= -4.607
X_α	= 20.57	N_β	= 2.92
$Z_{\dot{\alpha}}$	= -1.052	Y_p	= -2.191
$M_{\dot{\alpha}}$	= -.903	L_p	= -4.55
$Z_{\dot{i}_h}$	= -30.7	N_p	= -.426
$X_{\dot{i}_h}$	= 6.98	Y_r	= .92
$M_{\dot{i}_h}$	= -18.64	L_r	= 3.0
Z_q	= -3.01	N_r	= -.989
M_q	= -2.84	Y_{δ_r}	= .415
Z_u	= -.594	L_{δ_r}	= .732
X_u	= -.107	N_{δ_r}	= -2.401
M_u	= 0	$Y_{\delta_{sp}}$	= 0
$Z_{\delta_{sp}}$	= 4.98	$L_{\delta_{sp}}$	= 5.49
$X_{\delta_{sp}}$	= -.573	$N_{\delta_{sp}}$	= .185
$M_{\delta_{sp}}$	= .433		

Note: Spoiler derivatives are for one spoiler only (right wing).

2.3 Data Recording

An eight channel strip chart recorder was used to record various flight parameters during the evaluation flights. Among the variables monitored were: glide slope deviation, localizer deviation, spoiler deflection, throttle position, airspeed, pitch angle, vertical speed, normal acceleration, and altitude.

3. FLIGHT PATH CONTROL

The flight path control problem presented to the pilot in the landing approach depends on whether the approach is visual or ILS. Typical situations are illustrated in Figures 9 and 10. In the ILS approach, the pilot can compute and set up with the throttle the rate of descent he should have to stay on the glideslope (reference descent rate). His position, however, may be displaced from the glide slope as shown in Figure 9. The pilot is then required to perform some maneuver to get from point A to point B with initial and final descent rates equal. Two possible maneuvers are shown by lines 1 and 2. Line 1 shows the type of maneuver which would be possible in an aircraft which provided direct lift control, i.e., load factor control. The pilot would select a small negative increment in load factor, which would cause the flight path to curve downward toward the glideslope. At some midway point (point C), a positive load factor increment would be selected to pull up from the descent and again stabilize at the proper steady-state descent rate. It is seen that recovery from the maneuver is initiated before the aircraft is actually back on the glideslope. Therefore, there is no definite cue to tell the pilot when he has reached point C and should start pulling out. Of course, this might come naturally with some practice. Three control inputs are required: selection of negative "g" increment, selection of positive "g" increment, and return to unaccelerated flight. This type of maneuver would also be used by a pilot maneuvering with the stick(elevators).

Line 2 of Figure 9 shows a second possible maneuver connecting point A with point B. This path would be used by an aircraft which provided direct control of descent rate. In this case the pilot would select a higher than reference descent rate and simply maintain it until intercepting the glideslope. Then he would return to the reference rate of descent. In this case there is a positive cue as to when to recover from the "maneuver," and only two control inputs are required. This "maneuver" actually consists of connected segments of unaccelerated, steady-state flight, while maneuver 1 requires accelerated, non-steady-state flight. This maneuver (#2) would ideally be typical for a pilot controlling flight path with the throttle.

In the case of a visual approach the situation is simplified in that there is no set glide path or course to be followed. Thus, the flight path slope can be shallow or steep as long as it leads to the runway threshold. From experience, pilots of light aircraft know that a final approach begun at typical traffic pattern altitudes (about 800 feet) about a mile or so from the runway will result in a comfortable approach. Such visual approaches are often steeper than ILS approaches. This situation is illustrated in Figure 10. Point A represents an aircraft which has just turned onto its final approach in a slow descent established on the base leg of the traffic pattern. The only maneuver required to set up a proper approach is an increase in descent rate. This would place the aircraft on the desired flight path leading to the threshold. It would seem

that a maneuvering-type direct lift control system would be of little use in this situation, since maneuvering to a fixed glide path is not required.

The possible realization of these flight path control capabilities using wing spoilers is discussed in the following sections.

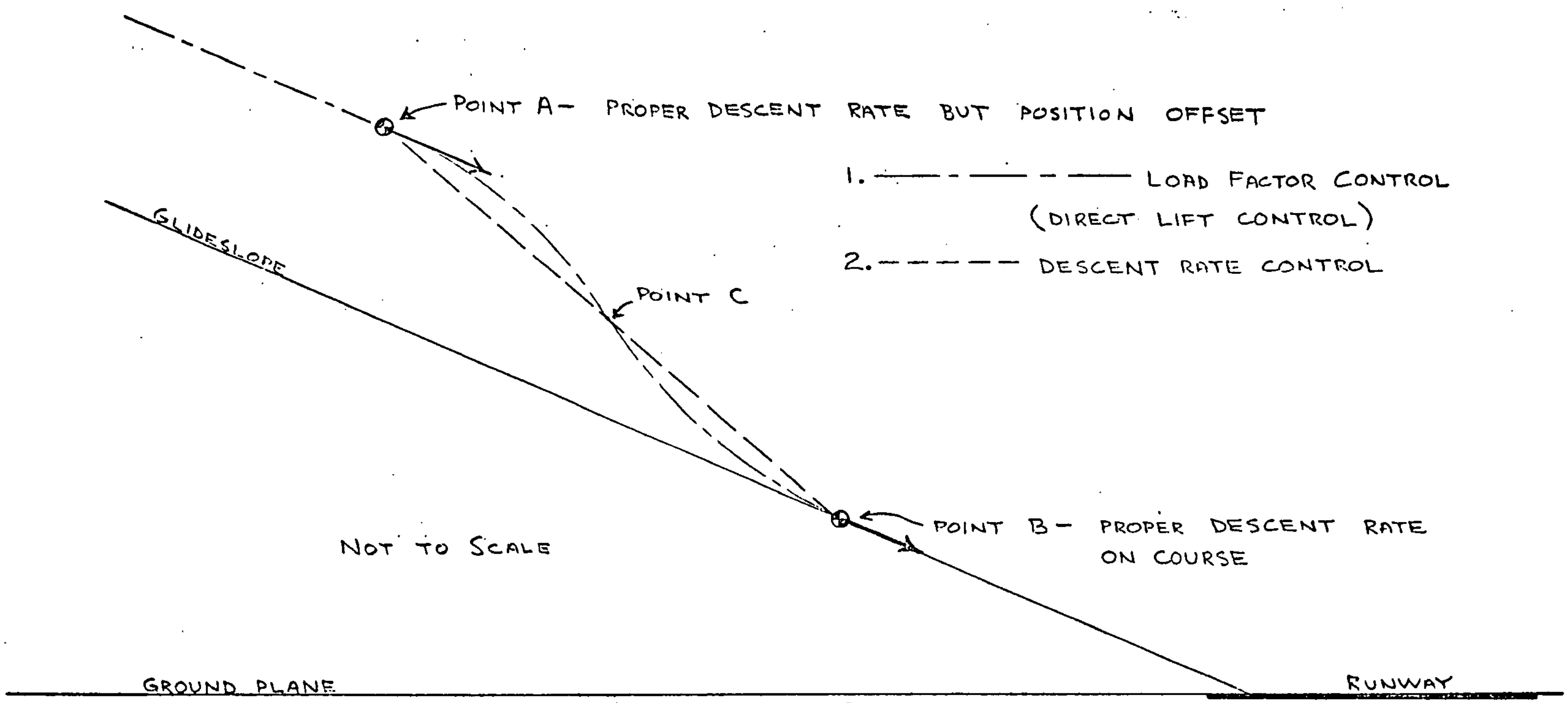


Figure 9

Typical ILS Approach Situation

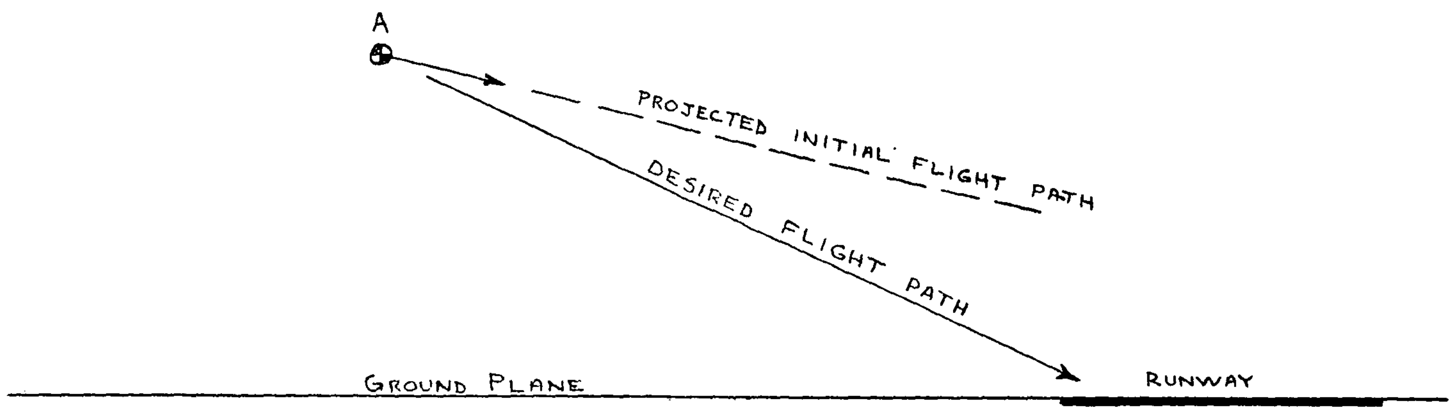


Figure 10

Typical Visual Approach Situation

4. AIRPLANE DYNAMIC RESPONSE

4.1 Airplane Response to Spoiler Deflection

This section describes the response of the modified Cardinal to spoiler inputs, as recorded on the simulator. For data-taking, the aircraft was trimmed for level flight, hands off, in smooth air. Spoilers were then deflected as desired using the bang-bang position command controller. No other longitudinal control inputs were made. The pilot used the rudders as necessary to keep the wings level. Since the flight controls in the simulator are essentially irreversible controls with artificial force-feel, hands-off flight is the same as stick-fixed flight.

4.1.1 Spoiler Pitching Moment

The pitching moment induced by a lift control defines the aerodynamic center location of the control lift increment through the expression

$$\bar{x}_{ac_{control}} - \bar{x}_{cg} = -\left(\frac{C_{m_\delta}}{C_{L_\delta}}\right)_{control.}$$

As shown by Pinsker in Reference 10, aircraft response to a given control lift input is largely determined by the aerodynamic center location of that control lift. If the control lift acts far forward, as with a canard, its effect is magnified by the wing-generated lift caused by the rotation to higher angle of attack. On the other hand, if the control lift aerodynamic center is far toward the rear, as with conventional tailplanes, the effect is

reversed. The net change in airplane lift is opposite in sign to the applied control lift, and usually much larger. Therefore, it is obvious that the pitching moment associated with a lift control such as spoilers is an important consideration in obtaining the desired response from the aircraft. The effect of spoiler pitching moment on the response of the modified Cardinal was investigated as described below.

4.1.1.1 Nominal Pitching Moment

The estimated spoiler pitching moment for the modified Cardinal with no elevator interconnect is $M_{\delta_{sp}} = +0.433$/radian. This will be called the "nominal" pitching moment. Figure 11 shows airplane response to a 10 second deflection of 20 degrees spoiler (1/2 of the available travel). The aircraft lost 30 feet of altitude and returned quickly and smoothly to level flight when the spoilers retracted. Pitch angle changed less than 1/2 degree and airspeed less than 1 ft/sec. Load factor increment was less than $\pm$ .04.

Figure 12 shows the response to a 20 second spoiler pulse. Again, the aircraft descended smoothly, this time 50 feet. The descent stopped within 3 seconds after the spoilers began retracting. Speed and pitch angle changes were less than 1 ft/sec and 1 degree, respectively.

The airplane response to a 20 degree step input is shown in Figure 13. The transition from level flight to descent took approximately 3 seconds, which is the time required for spoiler deflection. As before, speed and pitch angle variations were

small. Speed and pitch angle variations due to phugoid oscillation were less than 2 fps and 2 deg. (peak-to-peak), respectively. The aircraft deviated less than 5 feet from a steady 160 ft/min descent path. The aircraft trim speed changed by less than 0.5 fps.

It appears that the spoilers with nominal pitching moment make a satisfactory descent rate control. The aircraft maneuvers at constant speed, attitude, and load factor for all practical purposes; descent rate is the only motion variable significantly affected by the spoilers.

4.1.1.2 Zero Pitching Moment

$M_{\delta_{sp}}$ was next set to zero, and airplane response determined. Figure 14 shows the response to a 10 second spoiler pulse with zero spoiler pitching moment. Although the aircraft descended as much as 38 feet, the actual average altitude loss was approximately 20 feet. This is 2/3 the change achieved with nominal pitching moment. Speed and pitch angle changes due to phugoid oscillation were 7 ft/sec and 5.5 deg. peak-to-peak, respectively. This is enough to be objectionable considering the small (20 ft) altitude change actually involved. (Note that the load factor trace was not quite centered properly).

Airplane response to a 20 second spoiler pulse is shown in Figure 15. Again, an objectional degree of phugoid excitation is evident. Peak-to-peak speed and pitch angle excursions were again 7 fps and 5.5 deg. Altitude loss was 40 - 45 feet. During the descent phase of the maneuver, vertical speed actually reversed and

became positive for a time. This is an undesirable response. Zero pitching moment was considered to give unsatisfactory handling qualities.

4.1.1.3 Twice Nominal Pitching Moment

Going the other way, increased pitching moment was tried, in particular $M_{\delta_{sp}} = 2 \times (.433) = 0.866$ (two times the nominal pitching moment). Figure 16 shows airplane response to a 10 second spoiler pulse. Altitude loss was 28 feet with phugoid motion evident after level-off. The initial airplane response to spoiler deflection was a 3 degree pitch-up, 4 ft/sec loss in airspeed, and an increase in altitude. This is undesirable, even dangerous, if done at low speeds, as this example was.

Response to a 20 degree spoiler step is shown in Figure 17. The initial altitude increase and speed decrease can again be seen. Trim speed decreased by about 2.5 ft/sec, while pitch angle during the descent was actually about 1.5 degrees nose-up. The phugoid oscillation results in the "stairstep" descent seen in the altitude trace. The excess spoiler pitching moment in this case is unsatisfactory because the initial aircraft response to spoiler deflection is opposite to that intended.

4.1.1.4 "Pure" Direct Lift Control

Pinsker (Reference 10) defines pure direct lift control as a system by which the net change in aircraft lift is the same as the applied control lift. He shows that for this condition to be met the a.c. of the control lift must be as far forward of the aircraft

a.c. as the aircraft maneuver point is aft of the center of gravity. The maneuver point is defined by:

$$\bar{x}_{mp} = \bar{x}_{ac} - \frac{C_{m_q} \rho S \bar{c} g}{4 W} = 0.6412 \text{ for the modified Cardinal}$$

where $\bar{x}_{ac} = .5142$

and $\bar{x}_{cg} = .033$

Applying the above criterion, $\bar{x}_{ac_{control}} = -.094$, which implies $M_{\delta_{sp}} = -.0979/\text{rad}$. Theoretically this pitching moment would allow the spoiler system to generate sustained load factors for maneuvering. Figure 18 shows the airplane response to a 10 second control pulse with this pitching moment. While the initial load factor increment is -.08, it is quickly washed out by the speed increase caused by the descent. This effect would probably be even more pronounced without the drag of the spoilers. Phugoid excitation caused an initial 6 deg. peak-to-peak pitch angle excursion. To obtain and hold load factors different from 1.0, speed or angle of attack or both must be maintained at something other than the trim values. Maneuvering direct lift control is probably not possible without some form of speed control, since the airplane itself responds to a change in lift coefficient by seeking a new trim speed rather than maintaining a steady load factor. Because of this, the so-called pure DLC is probably not practical for implementation on the modified Cardinal.

4.1.1.5 Constant Lift Coefficient

In an attempt to minimize speed variation and phugoid excitation, the spoiler pitching moment was set to maintain a constant aircraft

lift coefficient. That is, the spoiler pitching moment caused the plane to maintain a higher angle of attack so that the increase in lift due to angle of attack equaled the loss in lift due to spoiler deflection.

For constant C_L, $L_\alpha(\Delta\alpha) = -L_{\delta_{sp}}(\delta_{sp})$

$$\Delta\alpha = -\frac{L_{\delta_{sp}}(\delta_{sp})}{L_\alpha}$$

For trim at the new α, $M_{\delta_{sp}}(\delta_{sp}) = -\Delta\alpha\ (M_\alpha) = \dfrac{L_{\delta_{sp}} M_\alpha}{L_\alpha}\ \delta_{sp}$,

$$\text{or } M_{\delta_{sp}} = \frac{L_{\delta_{sp}} M_\alpha}{L_\alpha} = \frac{4.98\ (-13.65)}{-144.5} \text{ for the Cardinal.}$$

Finally, $M_{\delta_{sp}} = 0.471$ for constant C_L.

This number is seen to be fairly close to the nominal $M_{\delta_{sp}}$ (0.433).

The airplane response to a 10 second spoiler pulse with constant C_L pitching moment is shown in Figure 19. The plane descended 30 feet and leveled off smoothly when the spoilers retracted with only a 2 ft. altitude overshoot. A slight phugoid motion is visible, but speed and pitch angle changes were small (1.2 ft/sec and 1.2 deg. peak-to-peak). This would seem to be a nearly ideal descent rate control.

Figure 20 shows a longer spoiler input. The time required to begin the descent is about the same time taken for spoiler deflection, so aircraft response is fairly rapid. A smooth descent with some phugoid motion resulted. Spoiler retraction was begun at the 98 ft. altitude point. Altitude overshoot from that point was about 6 feet while the spoilers were retracting, but the recovery altitude was approximately 98 feet. Overall, this system would rate good from a handling qualities point of view, since altitude and vertical speed are the only variables significantly affected by the spoilers. Pitch attitude and airspeed remain practically constant during the maneuver (within 1 ft/sec and 1 deg.), even though the control input used represents a sudden and relatively large deflection (20 deg., 1/2 the available travel).

4.1.2 Spoiler Drag and Lift Increments

The effects of spoiler lift and drag were investigated separately. Figure 21 shows airplane response to a 10 second spoiler pulse with no spoiler drag or pitching moment. In effect, this was a 10 second decrease in trim lift coefficient. As might be expected, the aircraft at first lost altitude, gaining speed in the descent (trim speed momentarily increased). When the spoilers retracted, most of the altitude loss was gained back, since the maneuver essentially traded potential and kinetic energy off against each other. The response had little in common with the response to the actual spoilers.

Figure 22 shows the airplane response to a 10 second pulse of

the nominal spoilers with spoiler drag zero (the load factor trace on Figures 21 and 22 is slightly off center). This input had little effect at all on the aircraft flight path (the initial altitude loss was only 7 feet). This would lead to the conclusion that spoiler drag is the major contributor to airplane response. To verify this, the effect of a speedbrake was recorded, as seen in Figure 23. Here $M_{\delta_{sp}}$ and $Z_{\delta_{sp}}$ are zero. The aircraft response is similar to that with the nominal or constant C_L spoilers (Figures 12 and 19). The real purpose of the spoiler system for flight path control, then, is the control of aircraft drag, or lift-drag ratio. This ratio determines the equilibrium flight path angle with constant thrust (Reference 11).

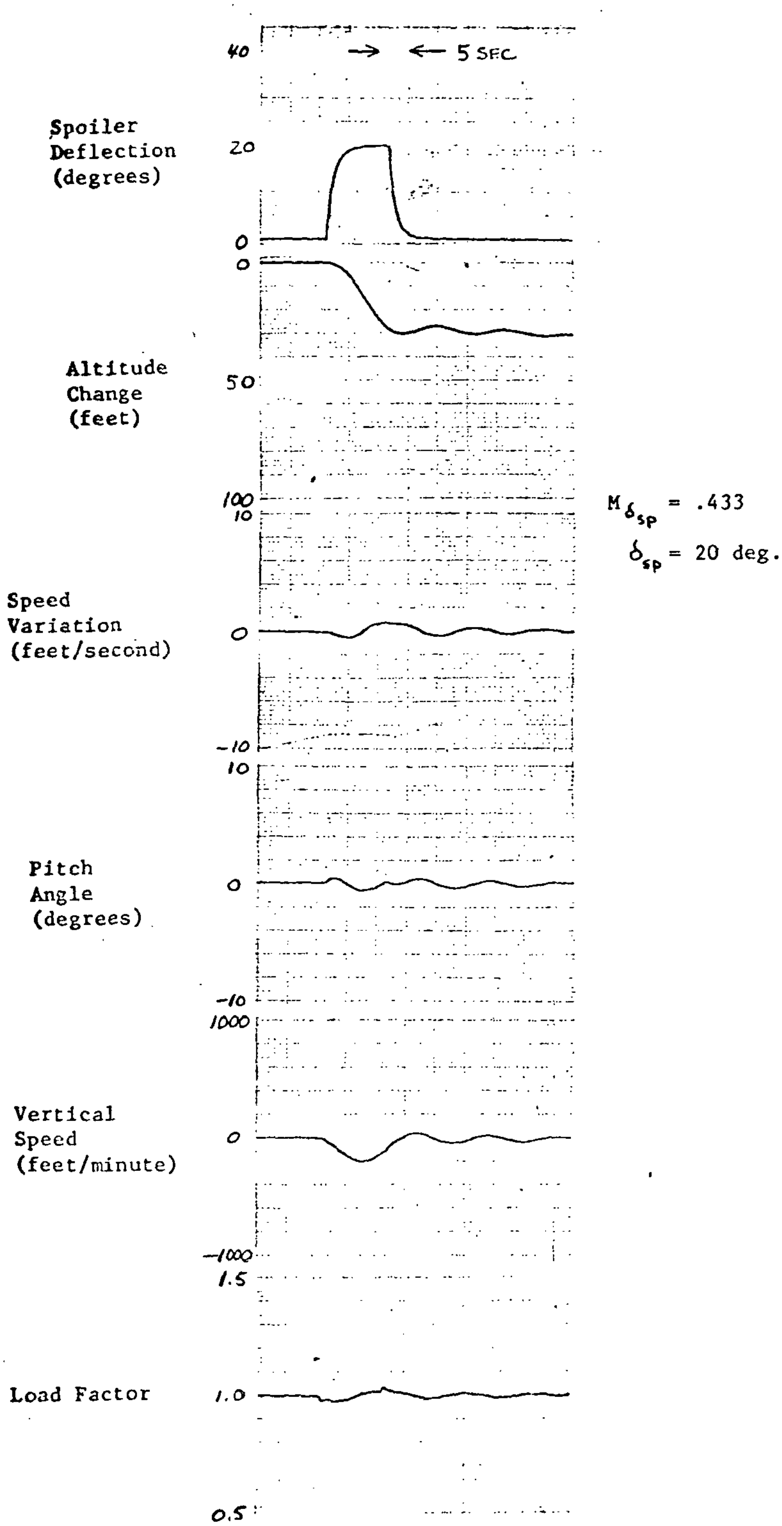


Figure 11

Aircraft Response to 10 Second Spoiler Pulse

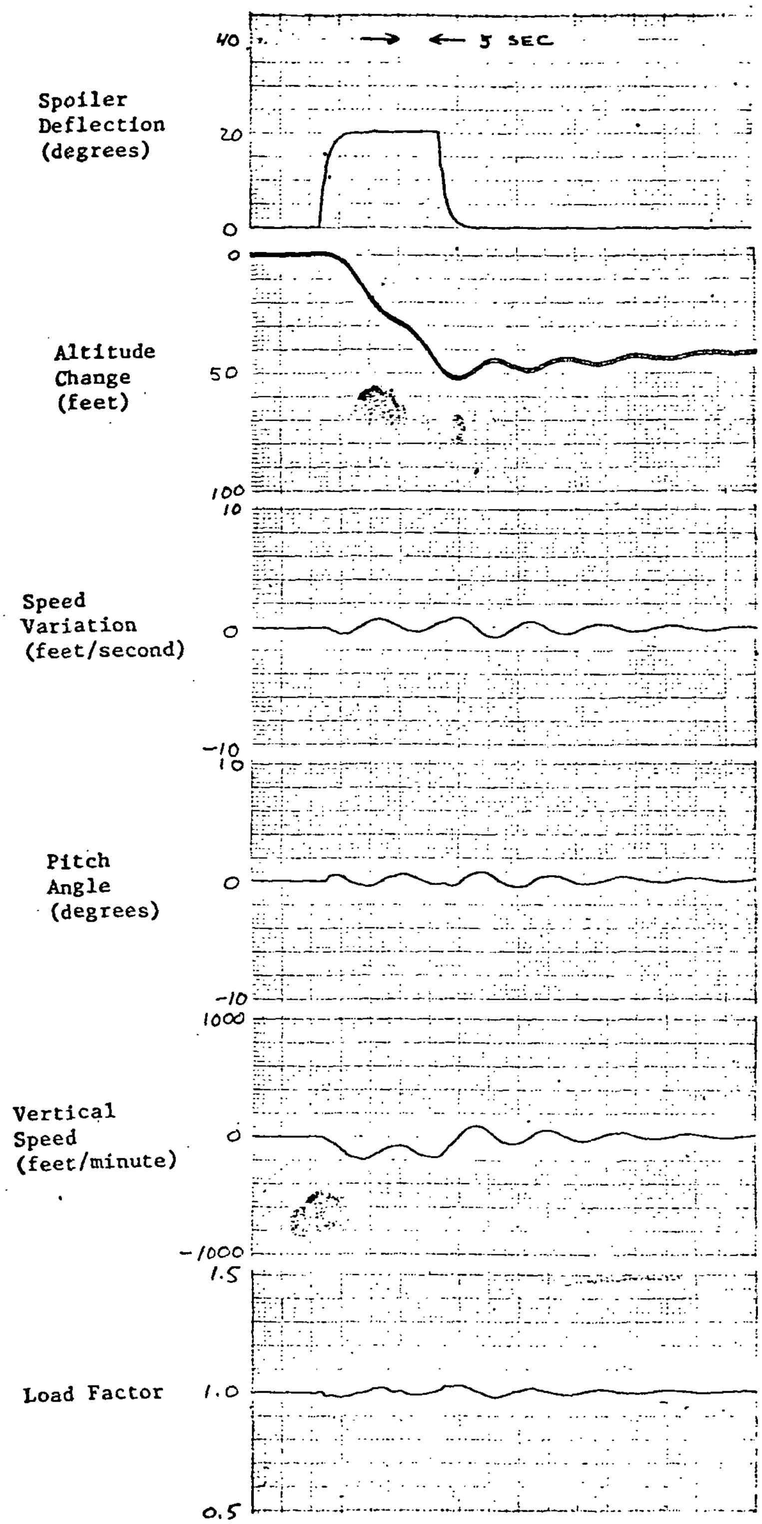


Figure 12

$M_{\delta_{sp}} = .433$

Aircraft Response to 20 Second Spoiler Pulse $\delta_{sp} = 20$ deg.

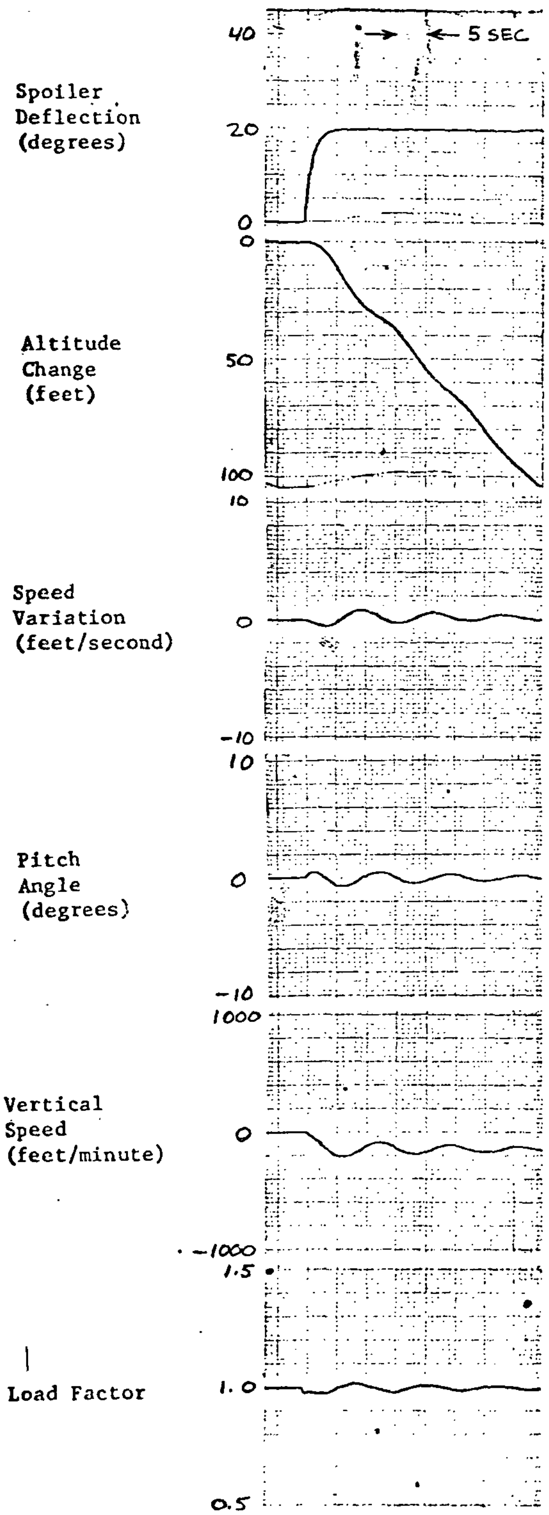


Figure 13

Aircraft Response to 20 Degree Spoiler Step $\quad M_{\delta_{sp}} = .433$

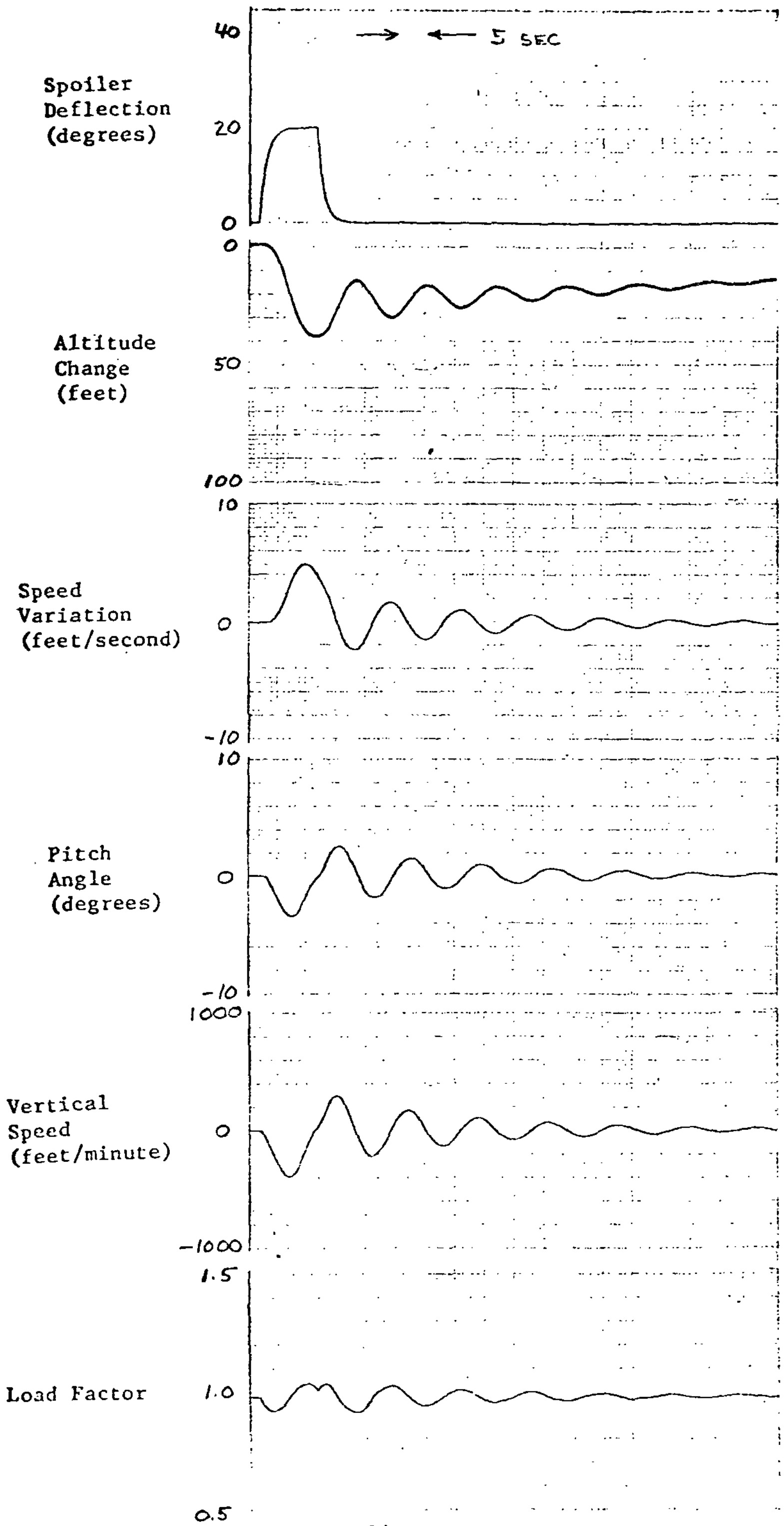


Figure 14

Aircraft Response to 10 Second Spoiler Pulse $M_{\delta_{sp}} = 0$

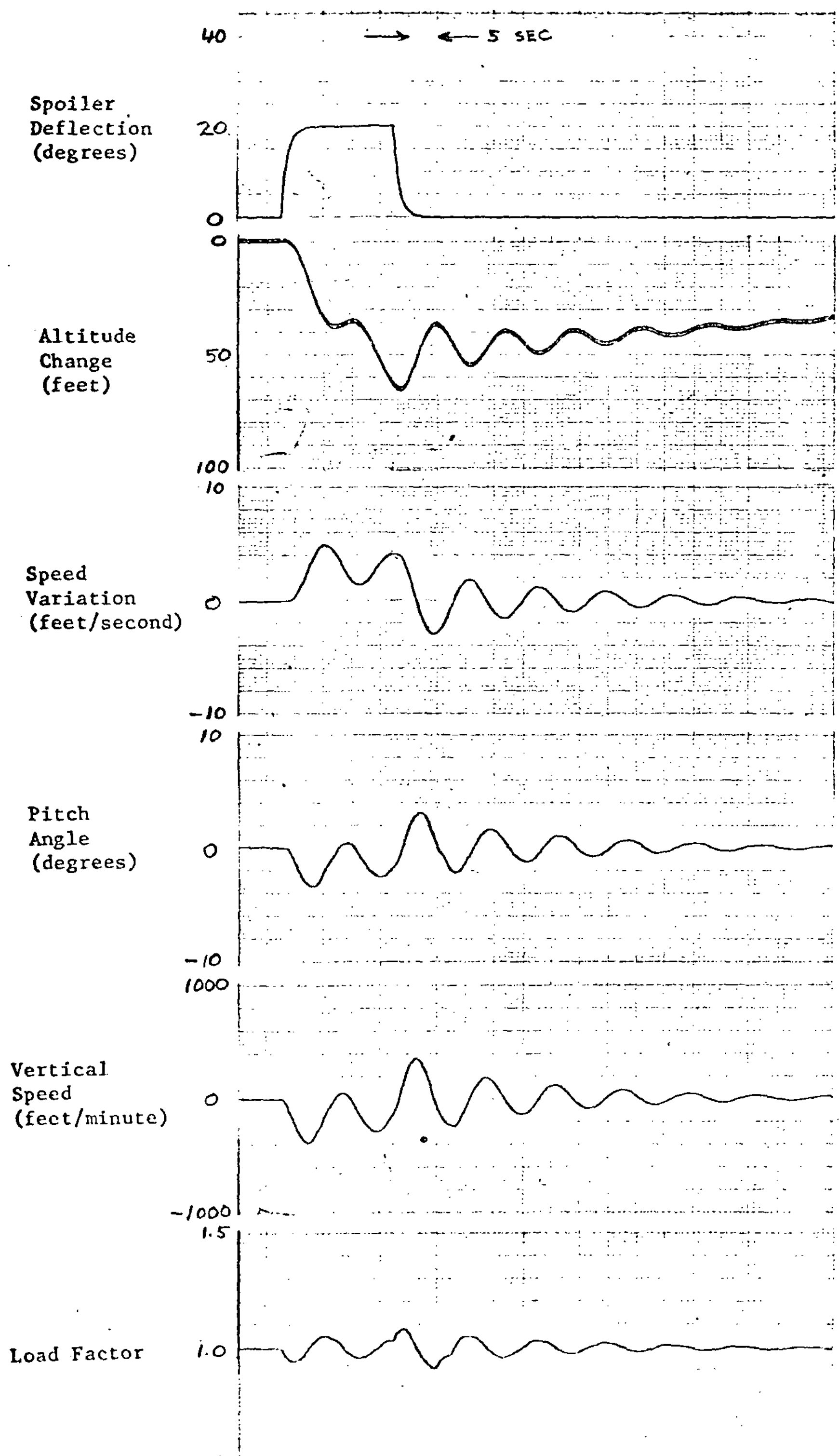


Figure 15

$M_{\delta_{sp}} = 0$

Aircraft Response to 20 Second Spoiler Pulse

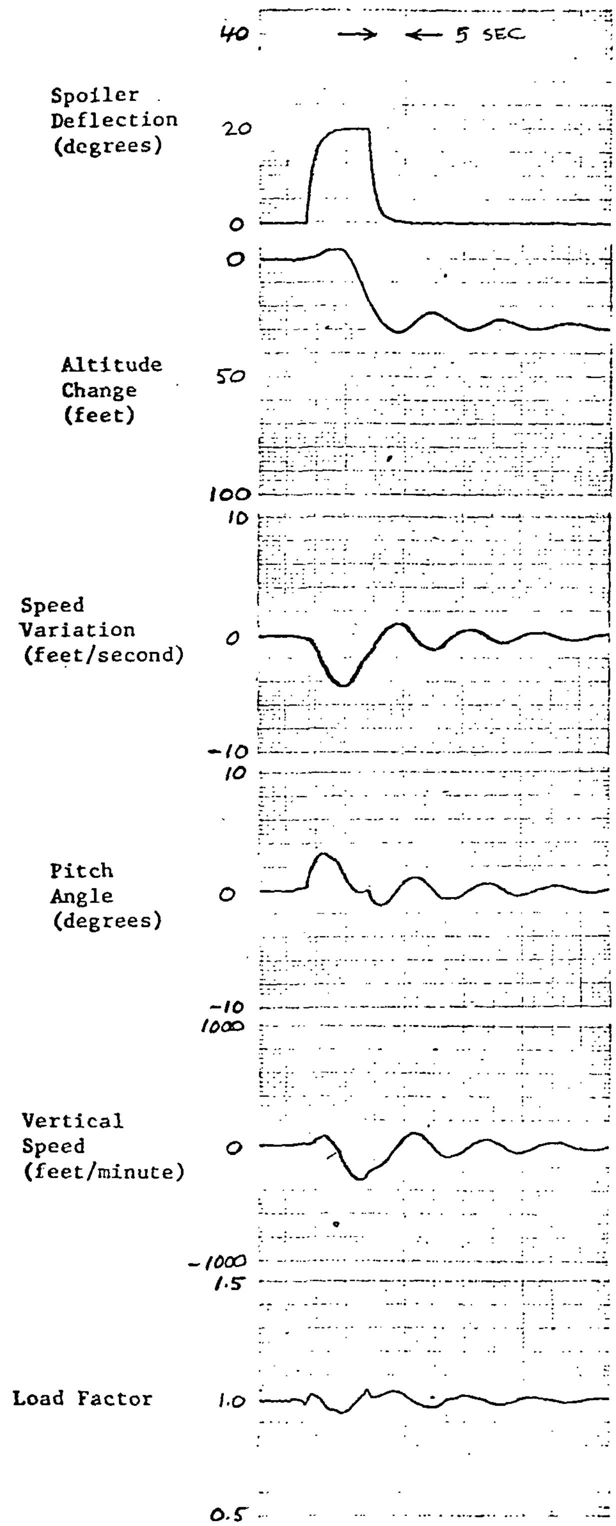


Figure 16

Aircraft Response to 10 Second Spoiler Pulse $M_{\delta_{sp}} = .866$

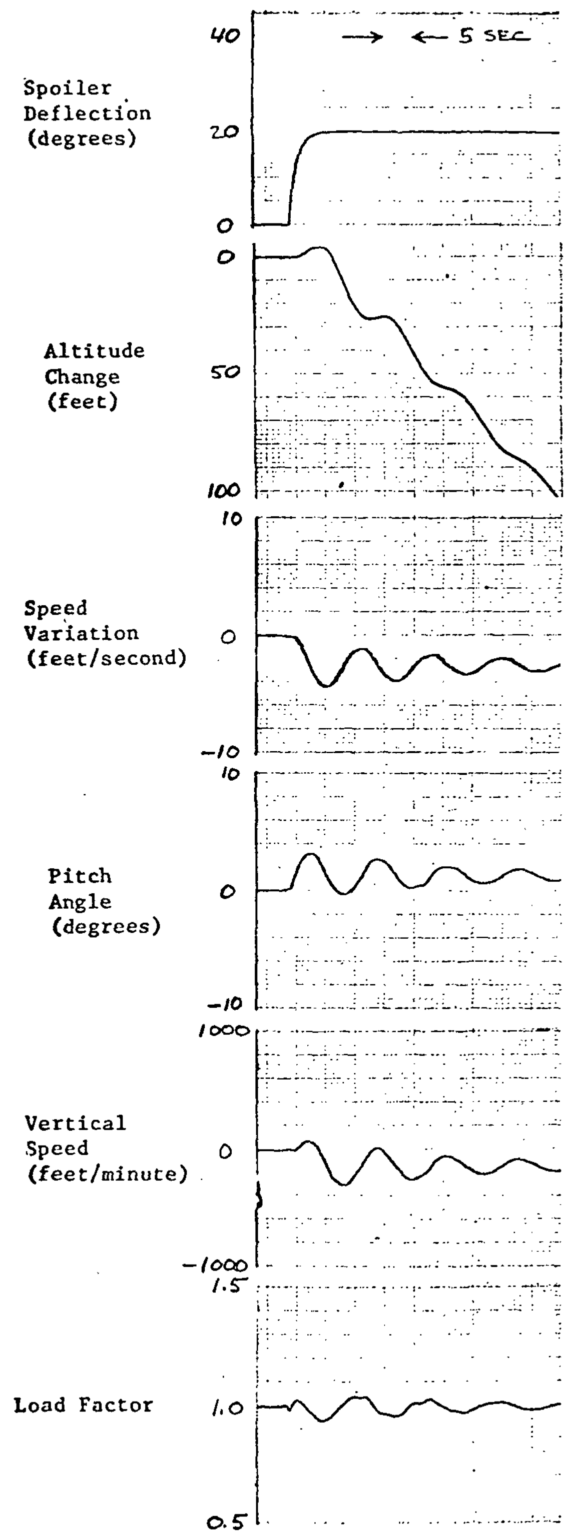


Figure 17

Aircraft Response to 20 Degree Spoiler Step $M_{\delta_{sp}} = .866$

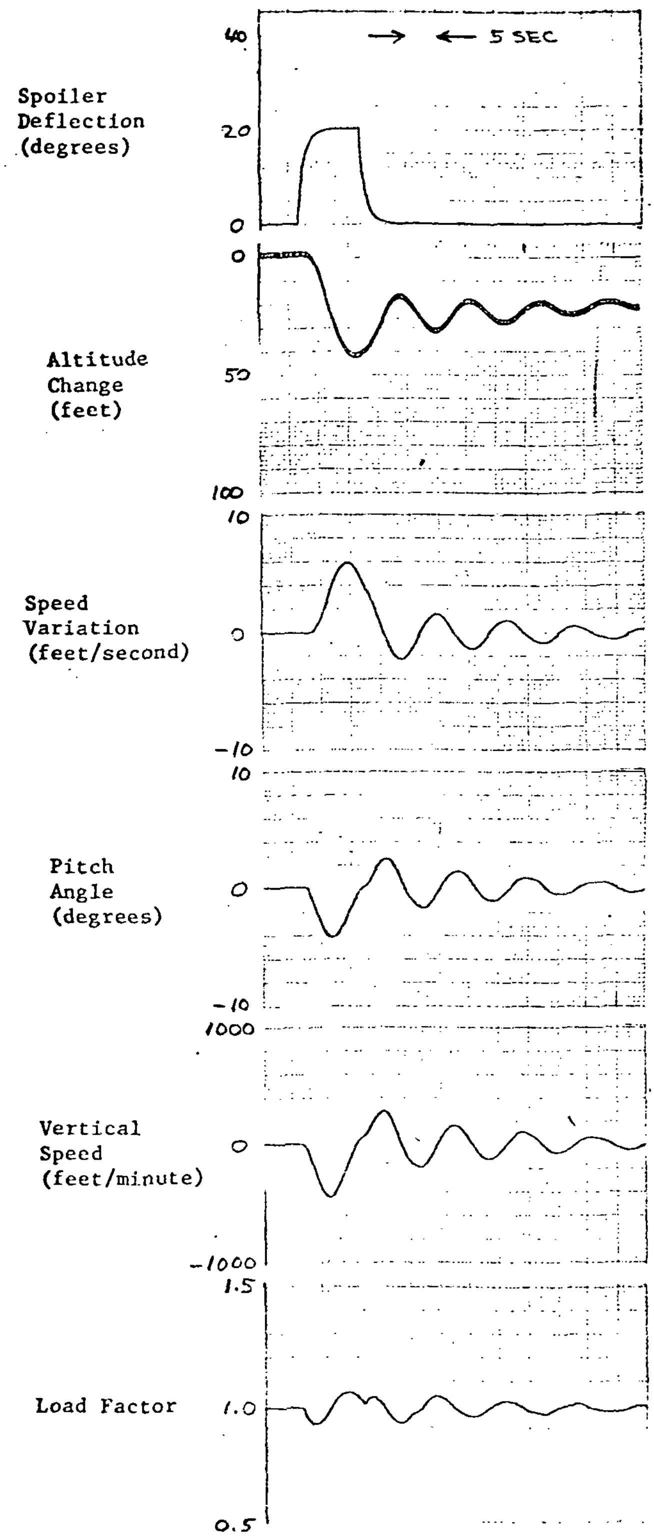


Figure 18

Aircraft Response to 10 Second "Pure DLC" Pulse $M_{\delta_{sp}} = -.0979$

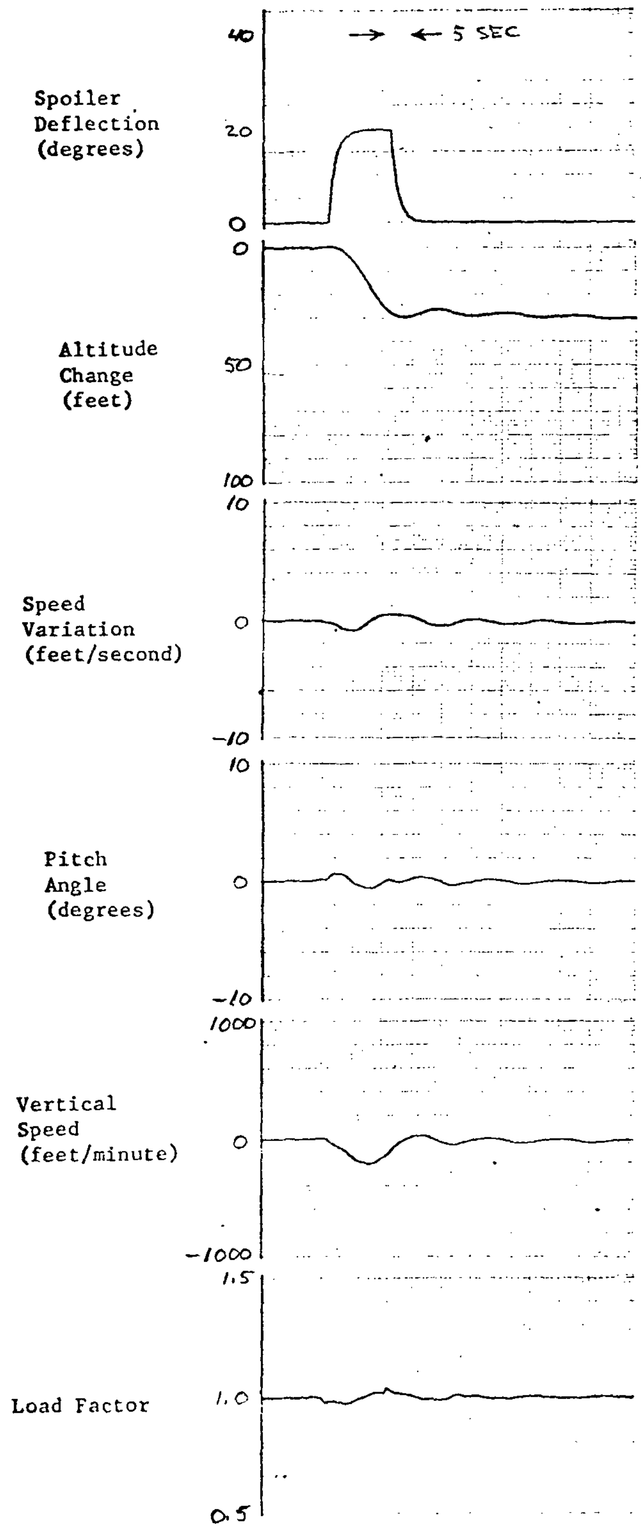


Figure 19

Aircraft Response to 10 Second Spoiler Pulse $M_{\delta_{sp}} = .471$

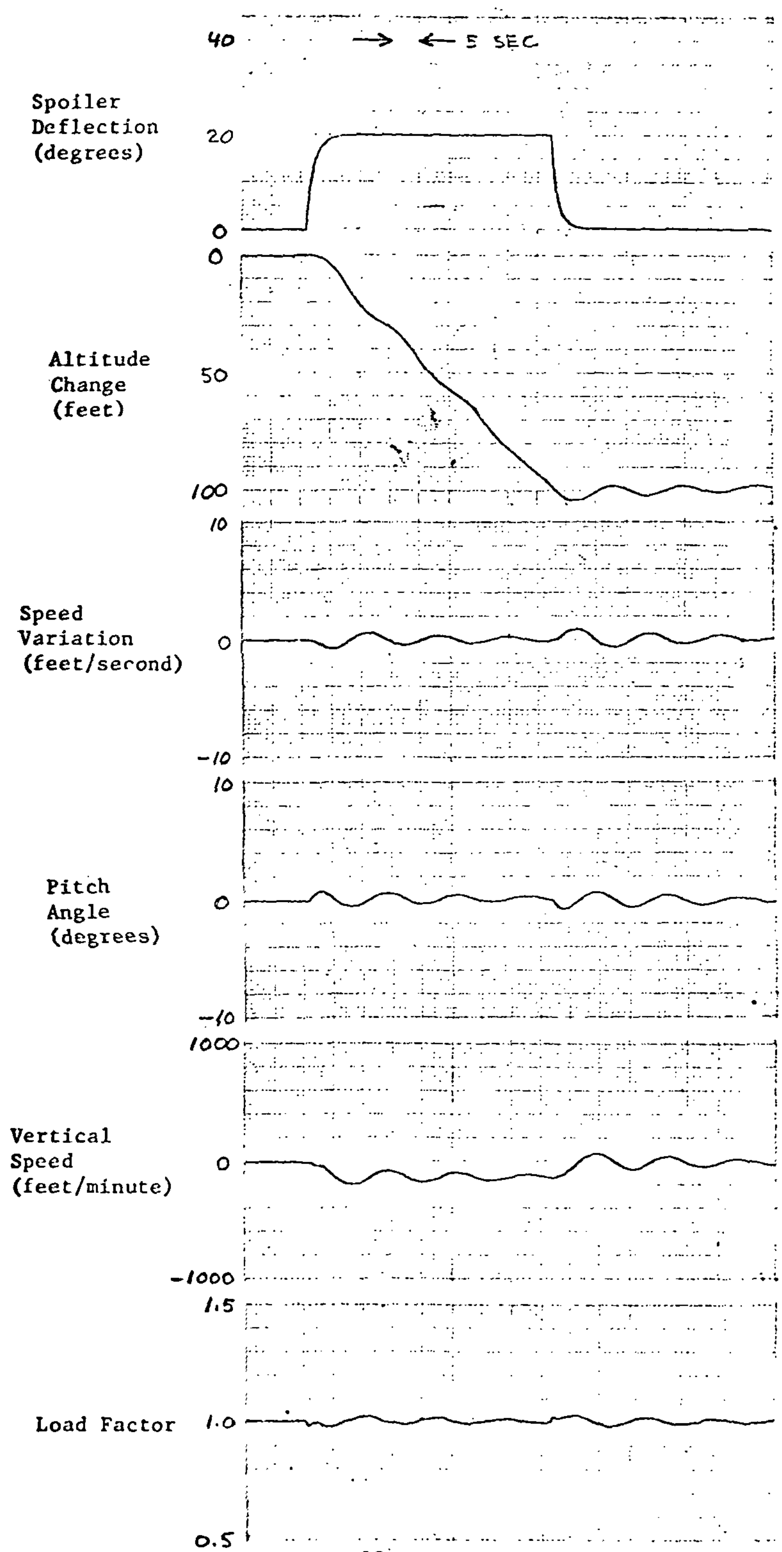


Figure 20

Aircraft Response to 20 Degree Spoiler Deflection $M_{\delta_{sp}} = .471$

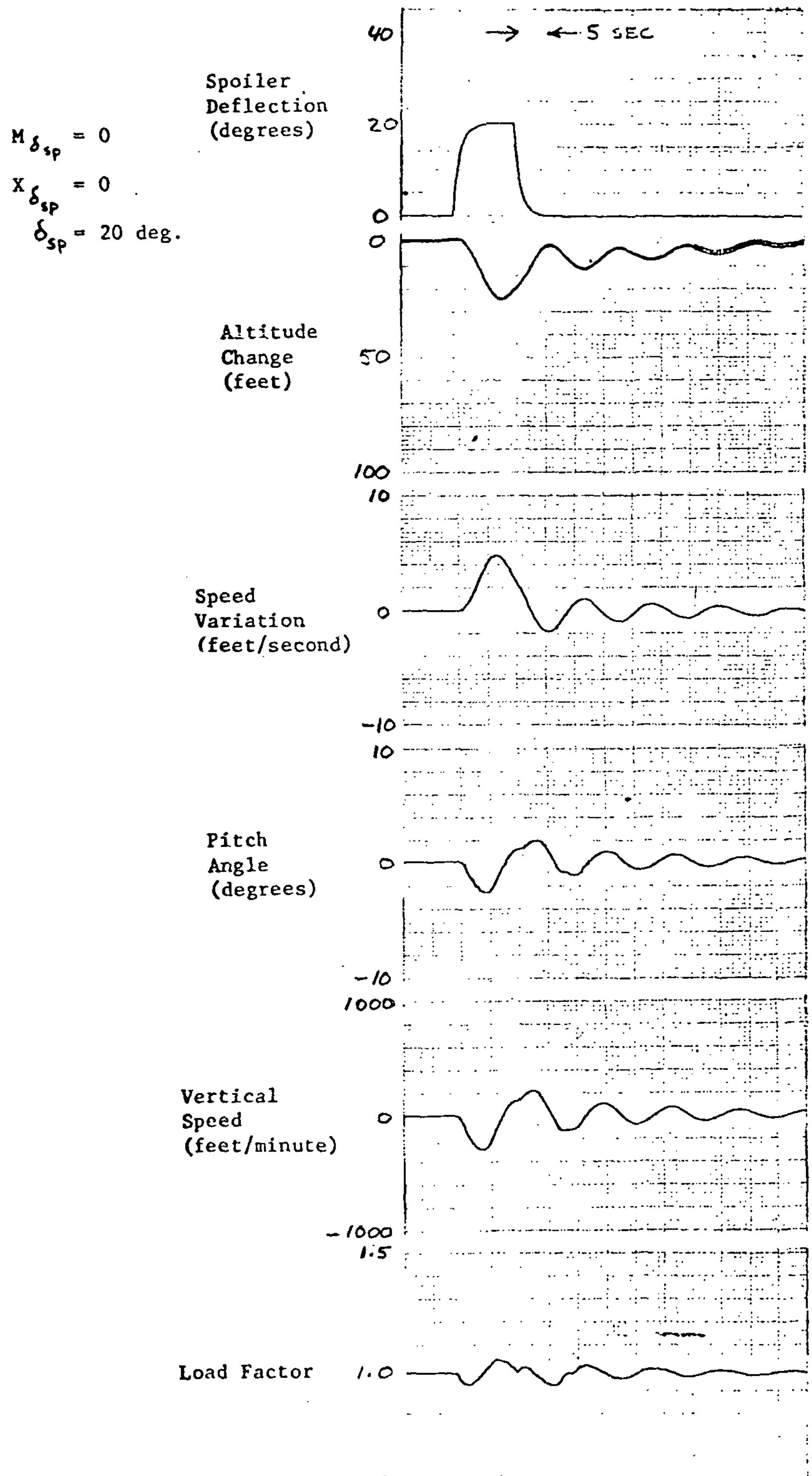
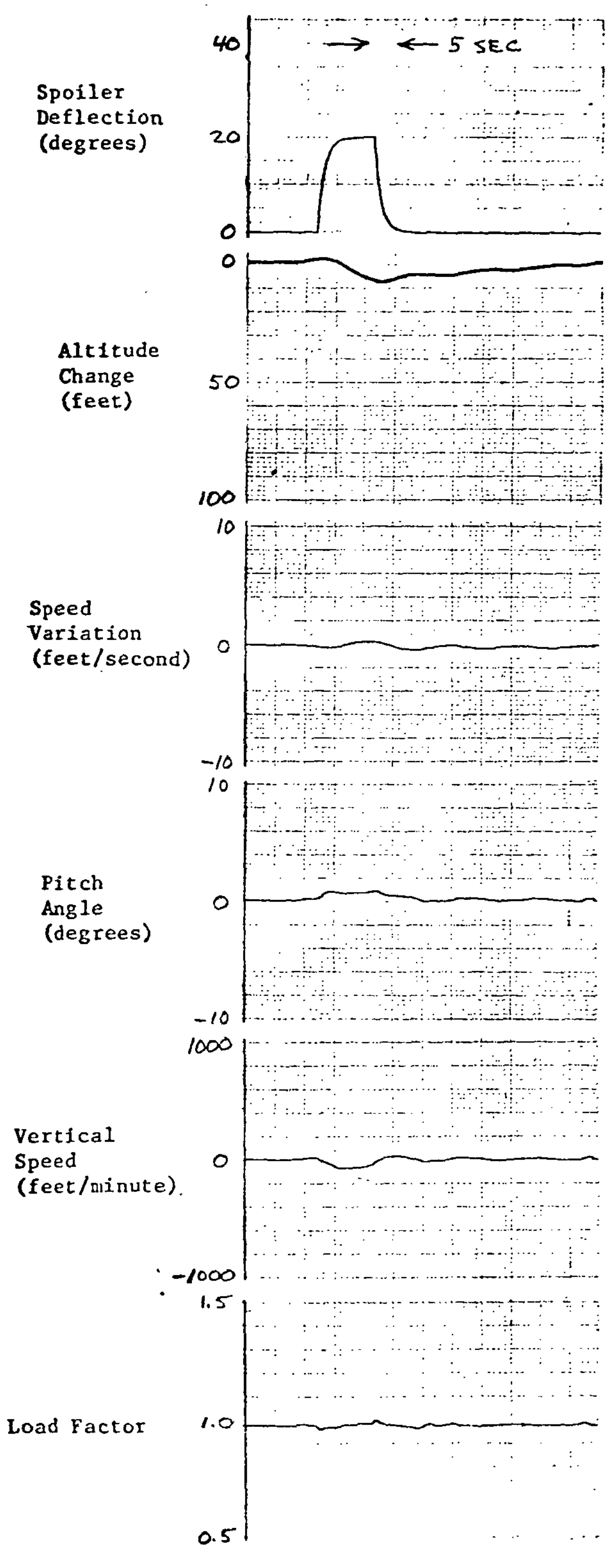


Figure 21

Aircraft Response to 10 Second Lift Pulse

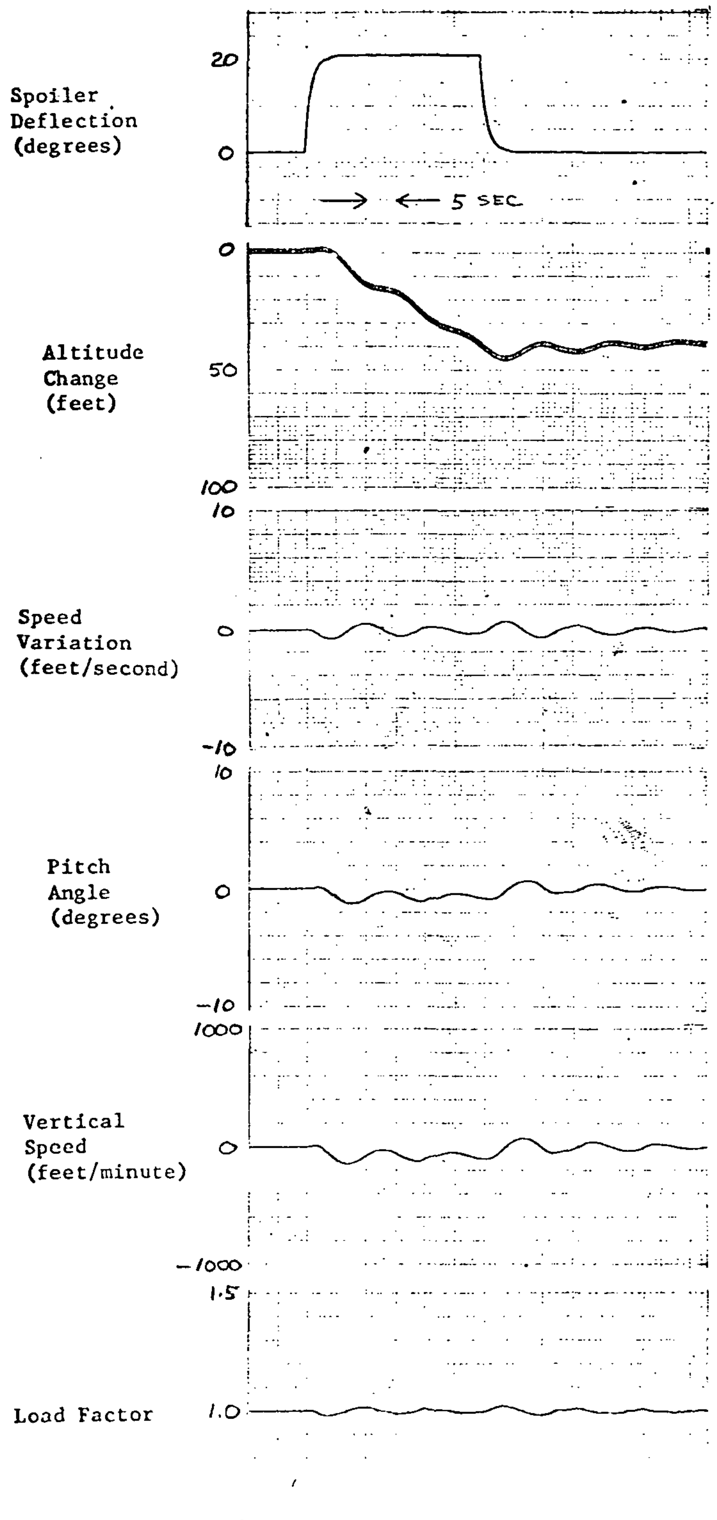


$M_{\delta_{sp}} = .433$

$X_{\delta_{sp}} = 0$

Figure 22

Aircraft Response to 10 Second Spoiler Pulse with Zero Drag



$M_{\delta_{sp}} = 0$

$Z_{\delta_{sp}} = 0$

Figure 23

Aircraft Response to Speedbrake

4.2 Airplane Response to Throttle

The airplane response to a change in power setting is shown in Figure 24. In the Cardinal there is a definite trim change with a power change. On the simulator this trim change was about 10 kt over the complete range of throttle settings. The throttle change used in Figure 24 was 200 RPM, which gave a descent rate about the same as 20 degrees of spoiler for comparison purposes. The power change excited the phugoid, and this caused the "stairstep" altitude trace. Note that at one point in the descent the aircraft is not descending at all, but holding altitude constant for about 4 seconds. The trim speed of the airplane also increases by nearly 2 ft/sec. While the handling qualities seen here (attitude and trim change, phugoid excitation) may not be particularly disturbing to a pilot, they are definitely inferior to those seen with the nominal or constant C_L spoiler systems. The spoiler systems performed the same maneuver with lower airspeed, pitch angle, and vertical speed excursions (less phugoid excitation).

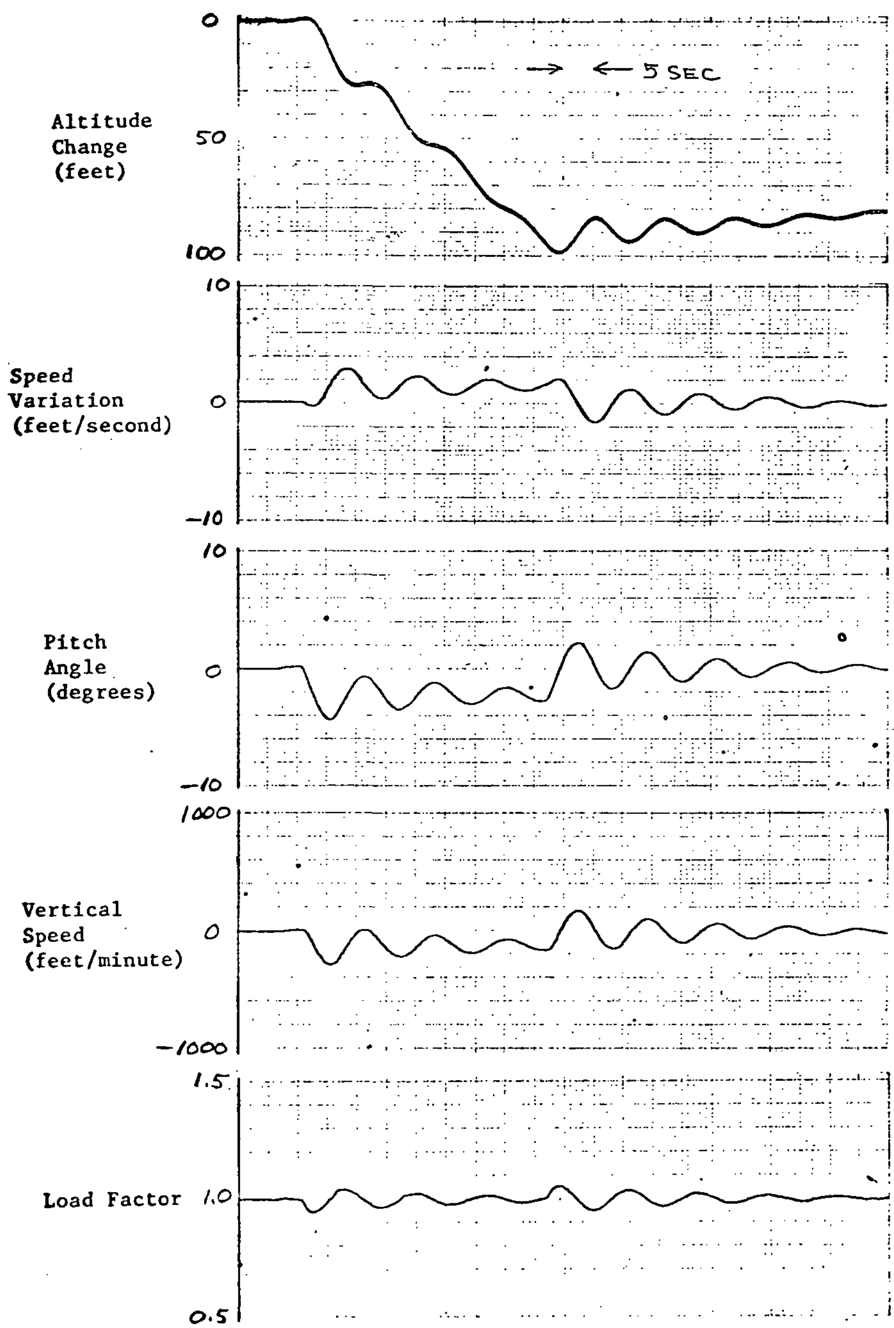


Figure 24

Aircraft Response to 200 RPM Throttle Change

5. INSTRUMENT LANDING SYSTEM APPROACHES

To evaluate the Cardinal spoilers as a flight path control in a realistic situation, more than 100 simulated ILS approaches were flown using 7 pilots with varied experience and training (see Table 2). Each pilot made several approaches using what he considered to be conventional control techniques (no spoilers). Along with these each pilot made a number of approaches using one or more of the spoiler controllers described in Section 2.1.3. In each case the setup was the same: the starting point of each approach was about one mile from the outer marker at 1500 ft. altitude, slightly displaced from the localizer centerline. The pilot was instructed to intercept the localizer while holding constant altitude. When the glide slope was intercepted at the outer marker he was to set up a descent and follow the ILS courses down to 200 ft. altitude (middle marker).

At the beginning of each flying session, the pilot was given time to make several approaches before data-taking was begun. This allowed him to get used to flying a simulator with no motion cues and to become familiar with the control and handling characteristics of the Cardinal. When a pilot flew a spoiler controller for the first time, he was allowed to make several practice approaches to get used to using it. Each non-practice approach was recorded for analysis, and the root mean square (RMS) glide slope deviation was computed for that part of each approach between the outer and middle markers. A description of each pilot's technique and performance and his comments and observations follows.

5.1 Conventional Approaches

A typical conventional approach flown by pilot A is shown in Figure 25. The vertical lines through the traces locate the outer and middle markers. This pilot was observed to use the throttle to control descent rate when following the glide slope. On Figure 25 each change in throttle setting is clearly marked by a phugoid oscillation followed by a noticeable change in trim speed and pitch angle. While the pilot remarked that the ILS approach was a fairly difficult task for him (he was not instrument rated), his glide slope tracking was relatively good. The RMS glide slope error for the approach shown was .055 deg.

Figures 26 and 27 show typical approaches by pilot B with and without turbulence. The two glideslope traces have similar characteristics typical of this pilot. He found the ILS approach to be quite difficult to do well because he had not mastered the throttle control technique required. His throttle changes seemed to be either too late or too large. Such difficulty might be expected, since pilot B was not an instrument rated pilot. This does indicate the difficulty of the task, however. The pilot's control inputs caused objectionable pitching oscillations and led to RMS errors for the two approaches shown of .27 deg. and .303 deg.

Pilot C, though he was not instrument rated, had had a lot of experience in the simulator. He had no particular difficulty making accurate ILS approaches using the throttle for descent rate control. Figures 28 and 29 show typical approaches without and with turbulence, respectively. Both are smooth, accurate approaches. None

of the pilots was really bothered much by the turbulence; they found that it was best to just ride with it instead of trying to fight it. RMS errors for the two approaches shown were .032 deg. and .049 deg. While the throttle was shown in Section 4.2 to be a less than ideal descent rate control, these approaches demonstrate that it is not impossible to make good approaches using it.

Pilot D was an active, instrument rated pilot who normally flew a light twin. He stated that he normally did not disturb his throttles after he began his descent at the outer marker. Any required corrections to descent rate were made with elevator trim. The reason for this was that in his plane friction in the throttles made it difficult to make small, accurate power changes. In addition, any power change would unsynchronize his propellors, which would be quite objectionable to passengers. Pilot D attempted to use this method for his simulated conventional approaches. If his initial power reduction was close to the proper one (to give reference descent rate), the approach went well, as shown in Figure 30. On this approach, the steadily increasing speed indicates that the pilot was trimming his nose down to compensate for a power setting which was a little too high. This technique obviously sacrifices precise speed control. Figure 31 shows an approach where the power setting was further off. This time no reasonable amount of trimming could keep the aircraft on the glide slope. This illustrates how necessary it is to get the power set correctly to fly a good approach.

Pilot E, like pilots A and C, used the throttle to control descent rate and consistently made good, well-controlled approaches.

A typical one is shown in Figure 32, for which RMS error was .083 deg.

Pilot F, a light twin pilot like Pilot D, also tended to use the elevator trim to adjust descent rate. Because he knew from experience about what power setting to use, all his conventional approaches were satisfactory. One is shown in Figure 33, with RMS error of .057 deg. A slight amount of nose-up trimming was done toward the end of the approach (note decrease in trim speed). Pilots D and F, who made heavy use of trim, were used to flying approaches at high speed because of fast jet traffic. The Cardinal, however, was set up for an approach speed of only 1.2 times stalling speed. During several approaches, the nose-up trim used to decrease descent rate caused the stall warning horn to come on. The implications of this are obvious. In an aircraft making a low speed approach precise airspeed control is vital, and excessive use of trim can lead to trouble.

Pilot G was a highly experienced professional pilot who used only throttle for descent rate control. His approaches were smooth and precise, as typified by Figure 34 (RMS error = .028 deg.), which shows a near-perfect approach. Unlike pilots D and F, Pilot G usually flew a single-engine light aircraft, which might explain why he didn't feel the need for using trim in addition to throttle for flight path control.

Pilot experience and technique largely determine the success of conventional ILS approaches. When the power is set correctly initially, the rest of the approach is relatively easy. But if the aircraft is some distance off the glide slope, a maneuver involving

throttle changes will probably be required to intercept the glide slope. Such a maneuver can be difficult to master. In the simulated approaches, all attempts to make any significant flight path change with trim led to large, undesireable speed and attitude changes, as might be expected.

Table 2

Evaluation Pilots

Pilot	License	Ratings	Hours	Familiar with Simulator?
A	Private	ASEL	350	Yes
B	Private	ASEL	350	No
C	Private	ASEL	75	Yes
D	Commercial	Instrument Multi-engine	1000	No
E	Private	ASEL	150	Yes
F	Commercial	Instrument Multi-engine	1500	No
G	ATR	Instrument Multi-engine	7000	No

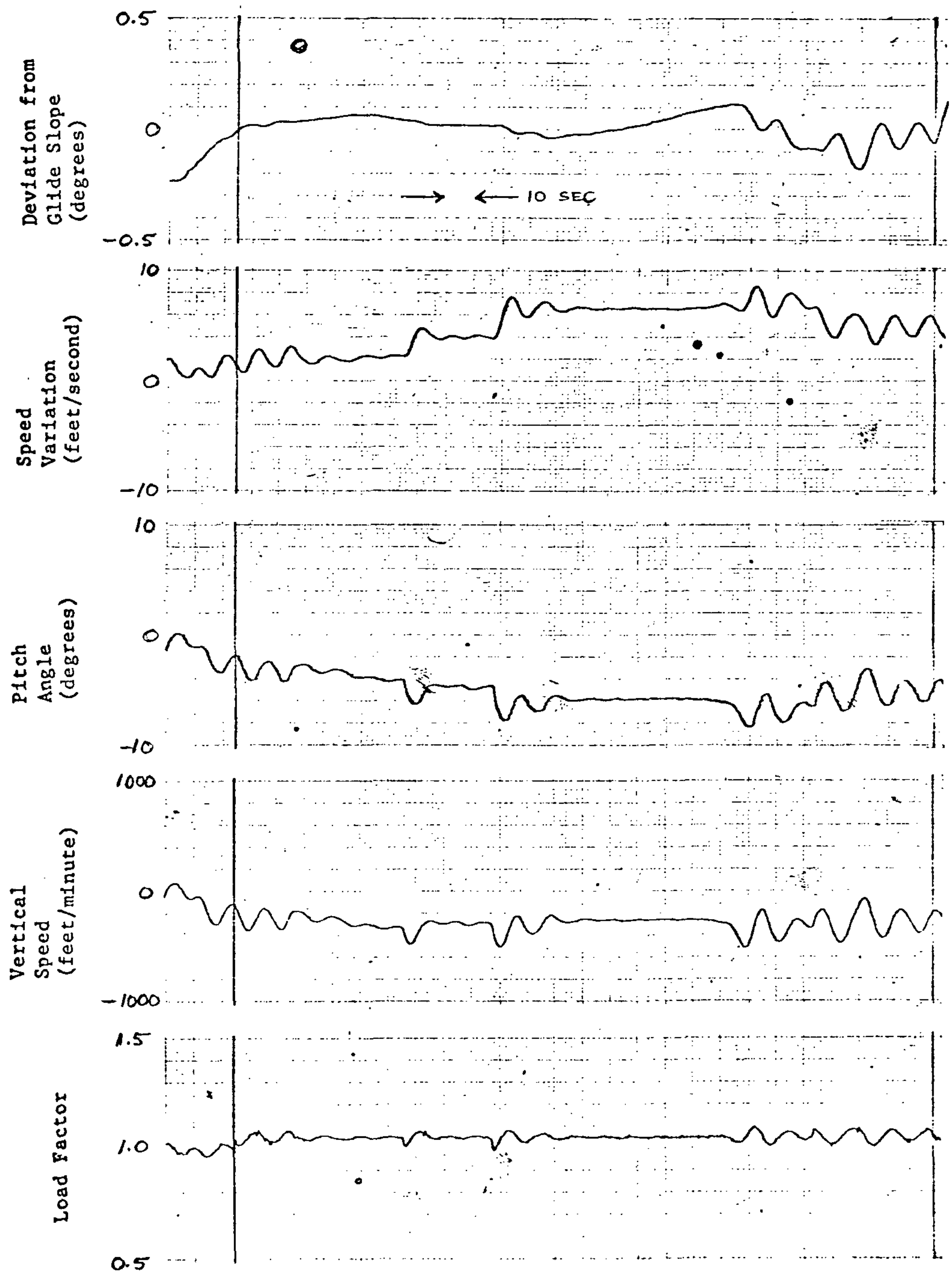


Figure 25

Conventional ILS Approach, Pilot A

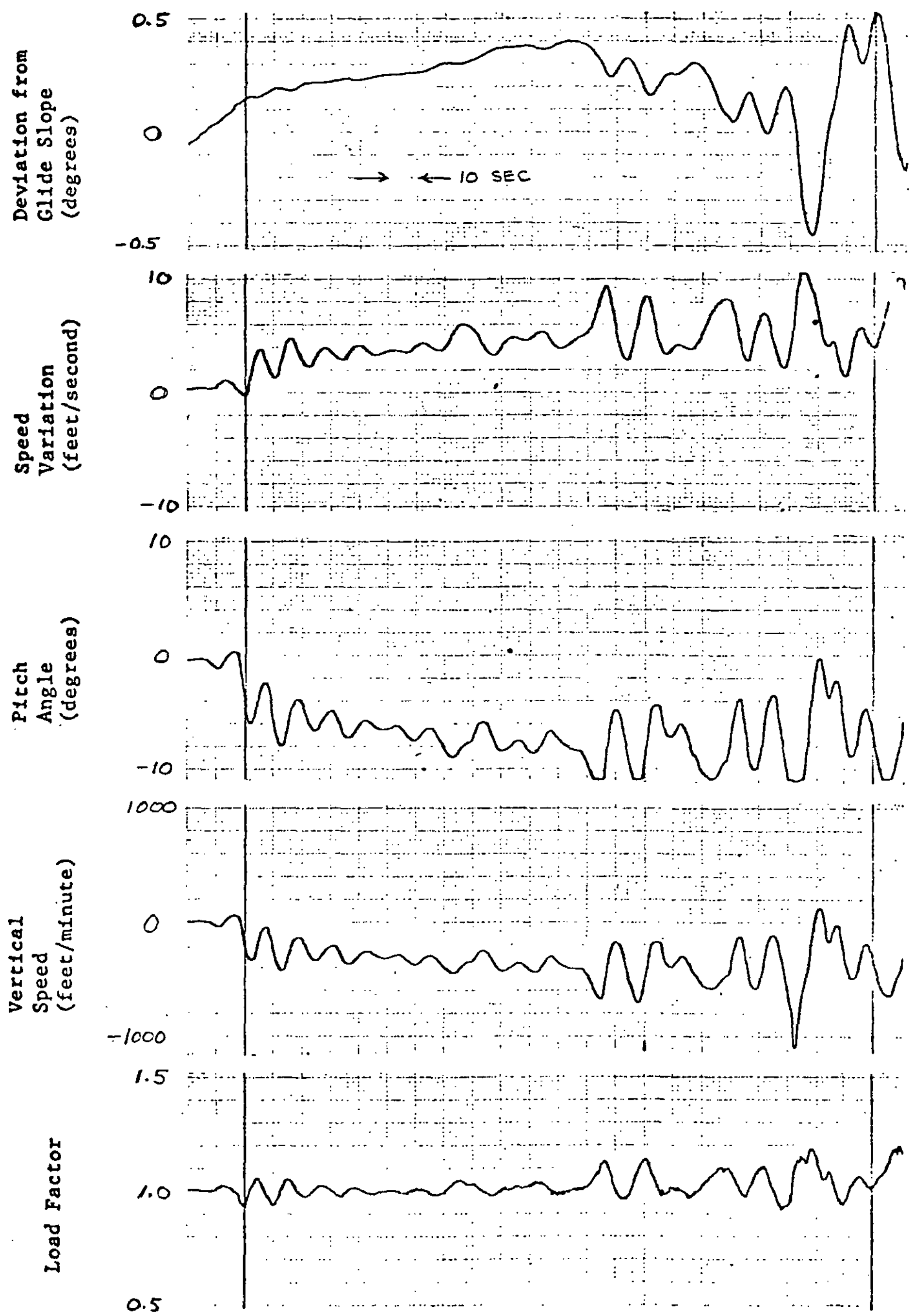


Figure 26

Conventional ILS Approach, Pilot B

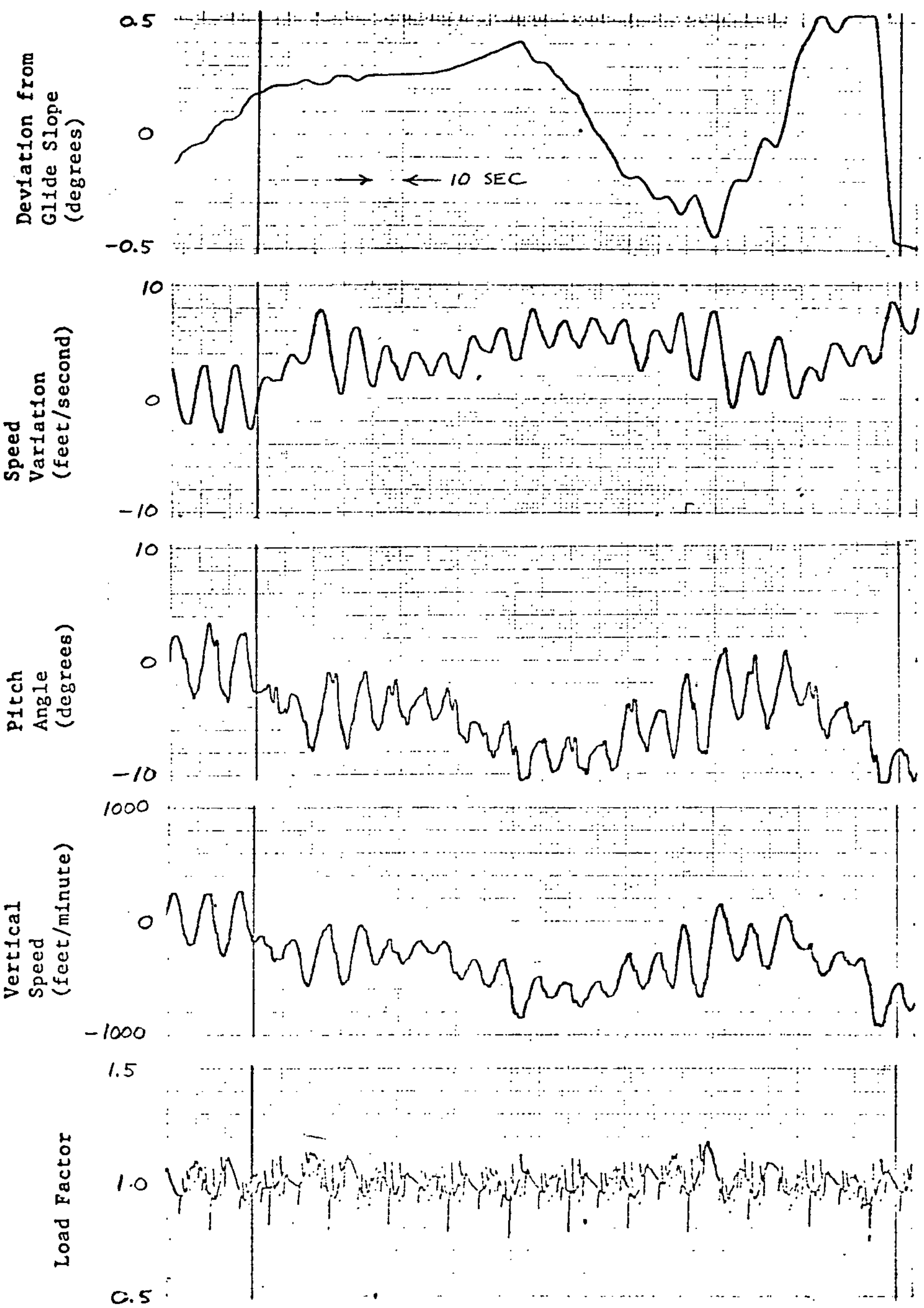


Figure 27

Conventional ILS Approach with Turbulence, Pilot B

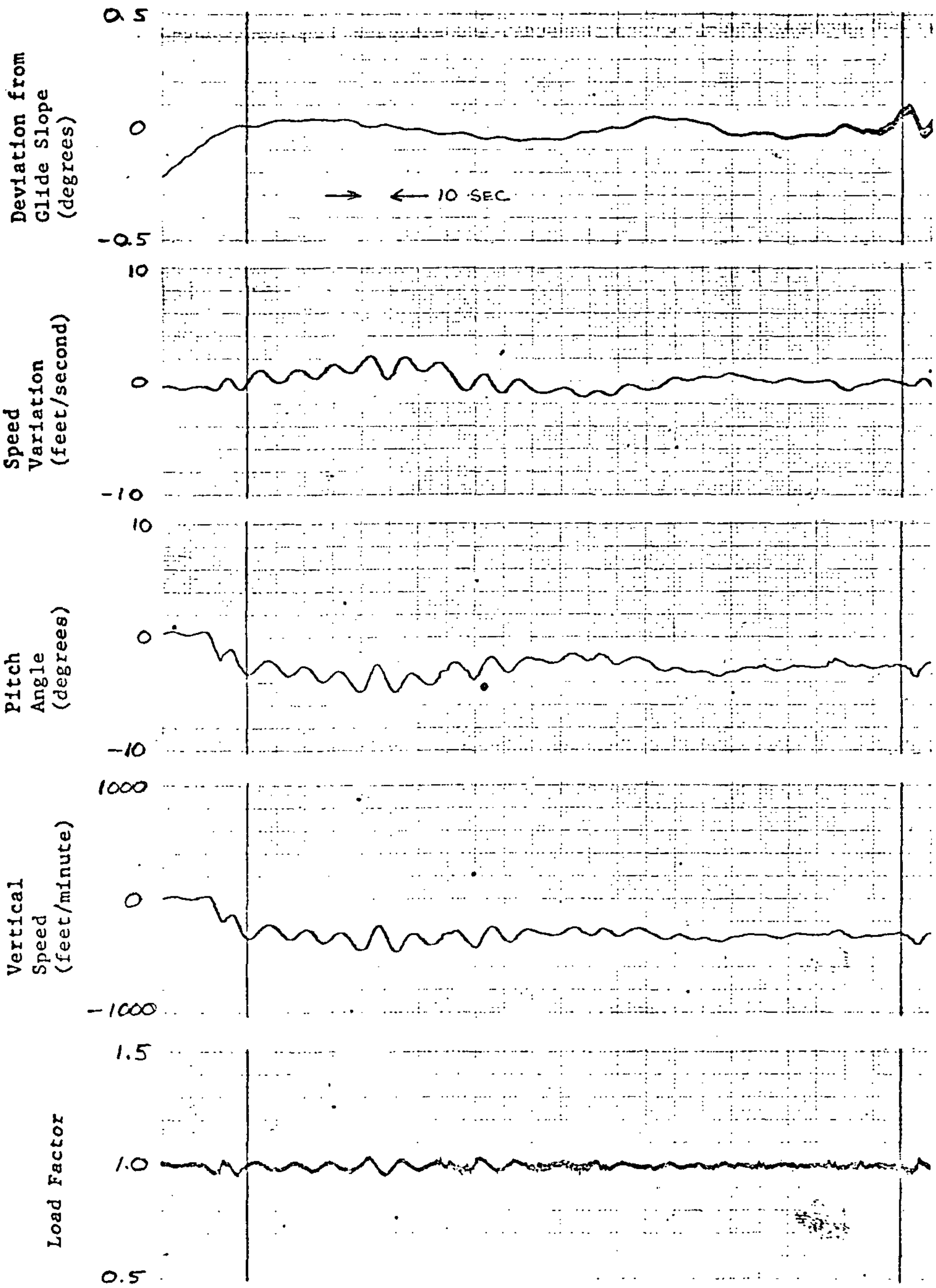


Figure 28

Conventional ILS Approach, Pilot C

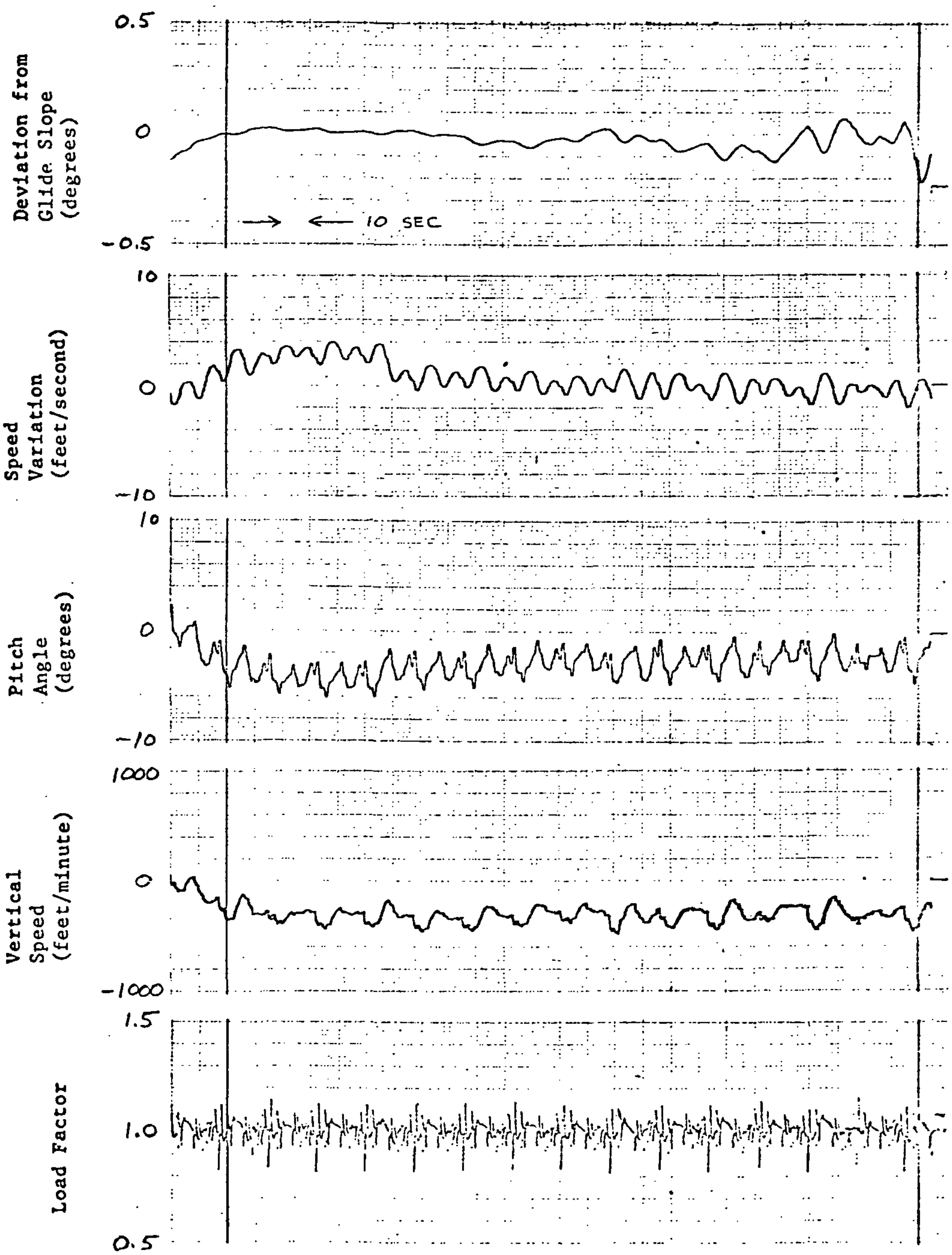


Figure 29

Conventional ILS Approach with Turbulence, Pilot C

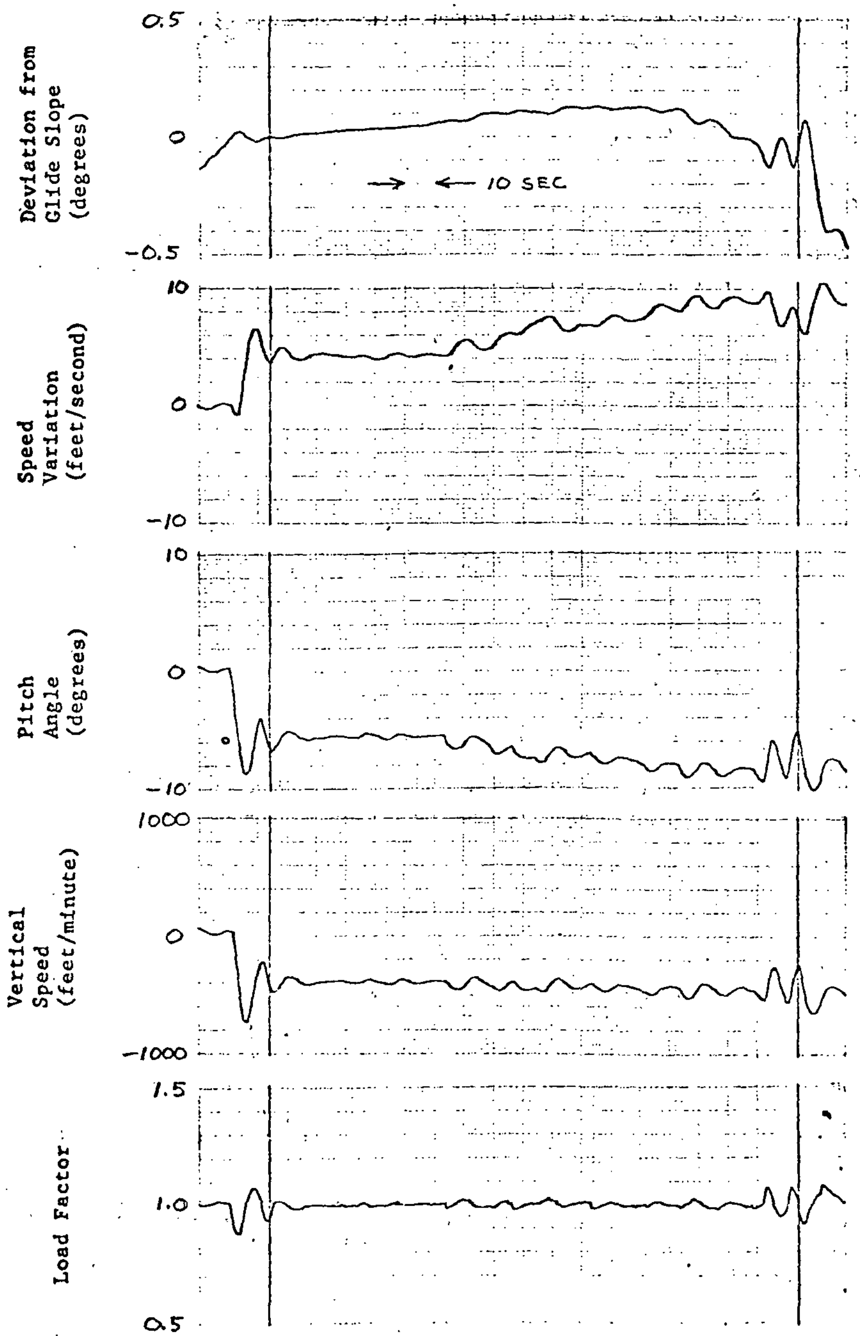


Figure 30

<u>Conventional ILS Approach, Pilot D</u>

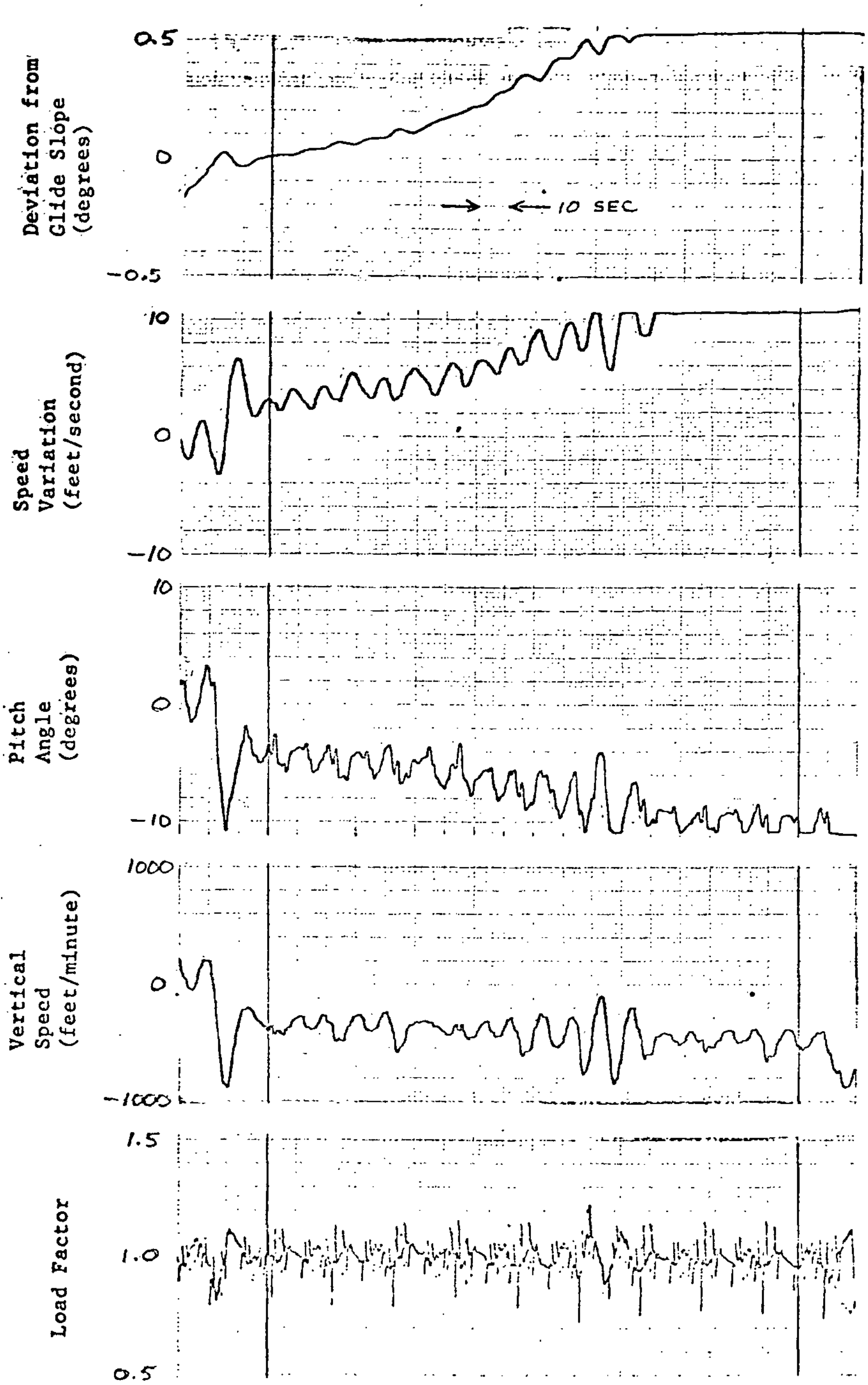


Figure 31

Conventional ILS Approach with Turbulence, Pilot D

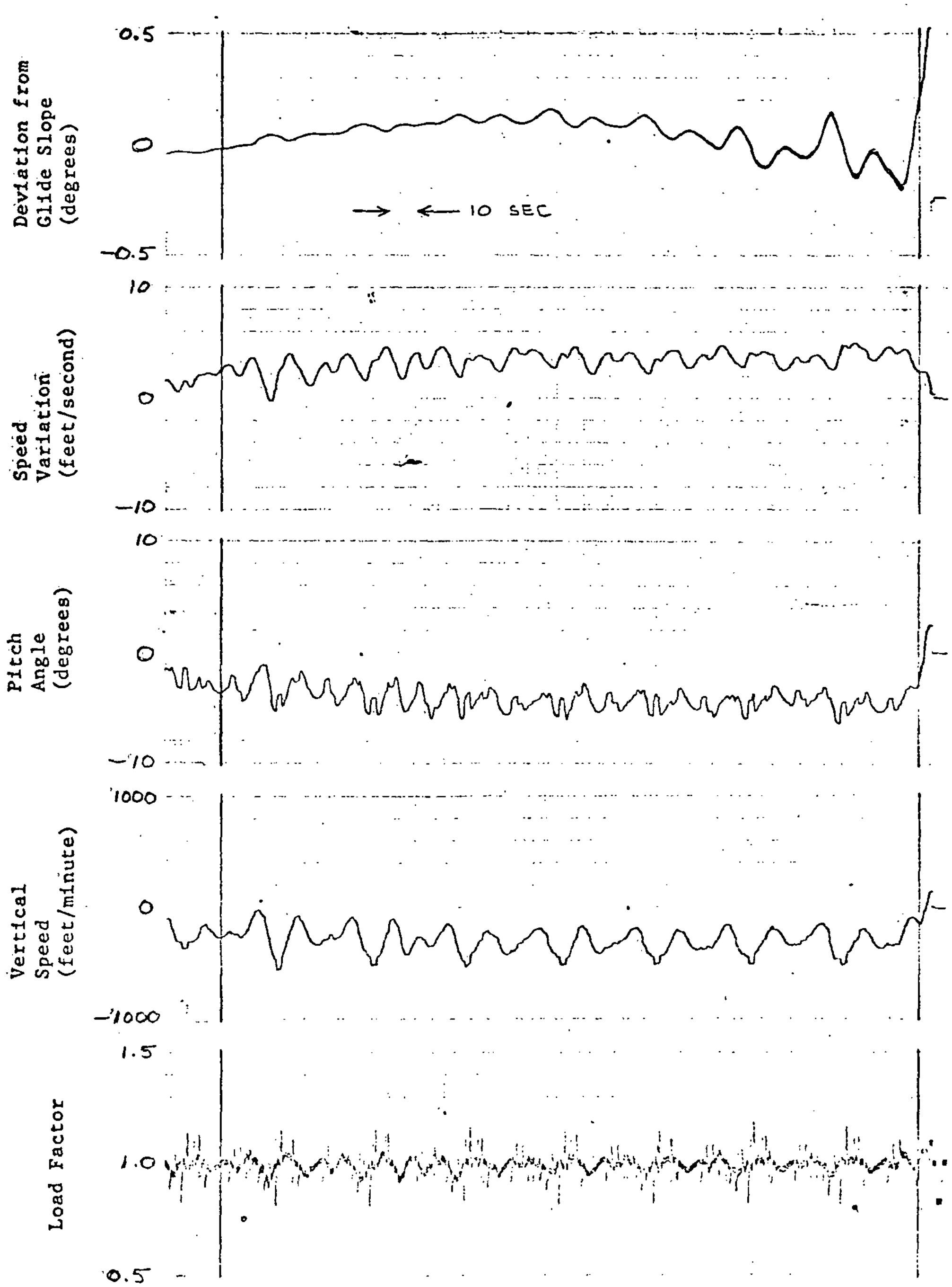


Figure 32

Conventional ILS Approach with Turbulence, Pilot E

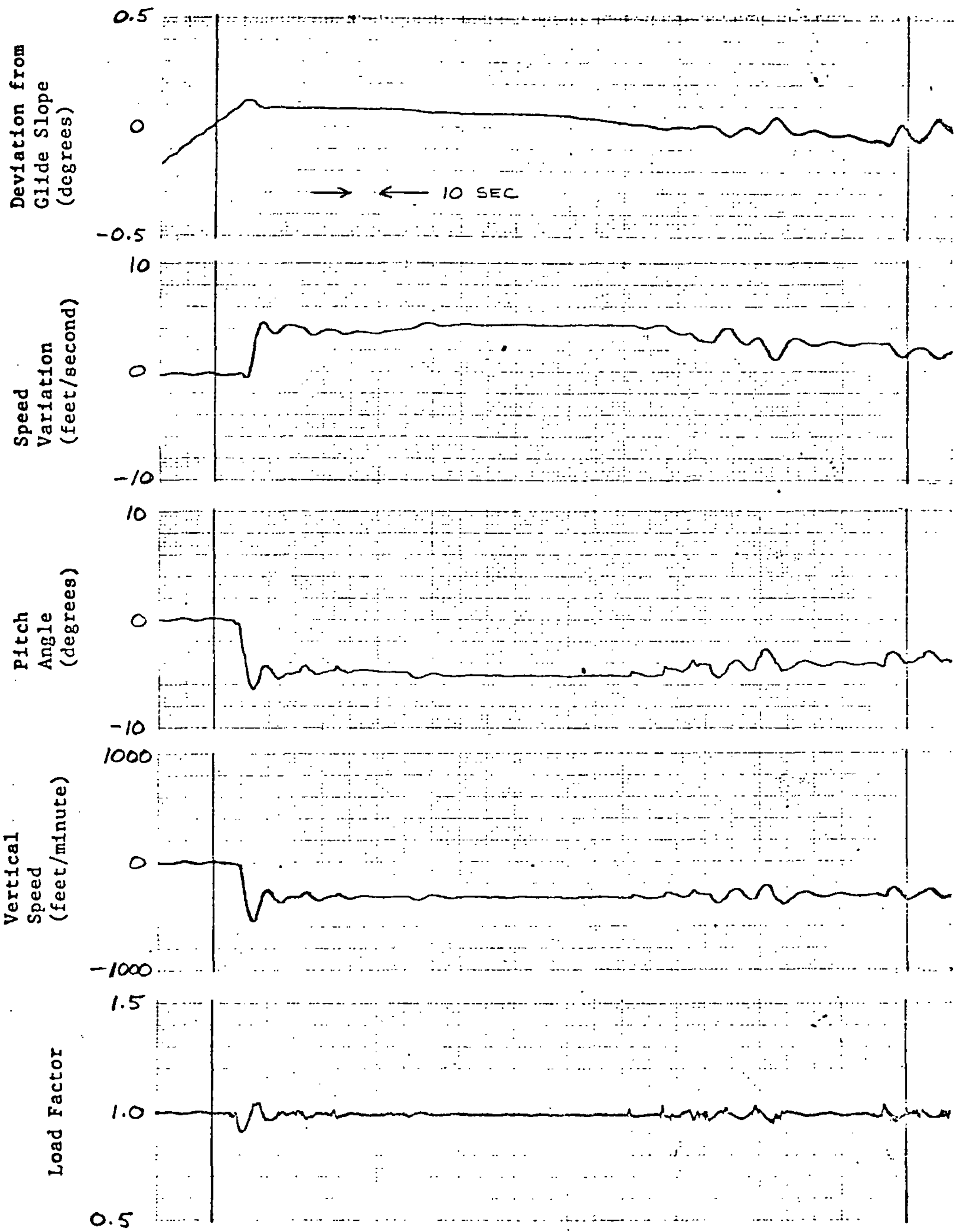


Figure 33

Conventional ILS Approach, Pilot F

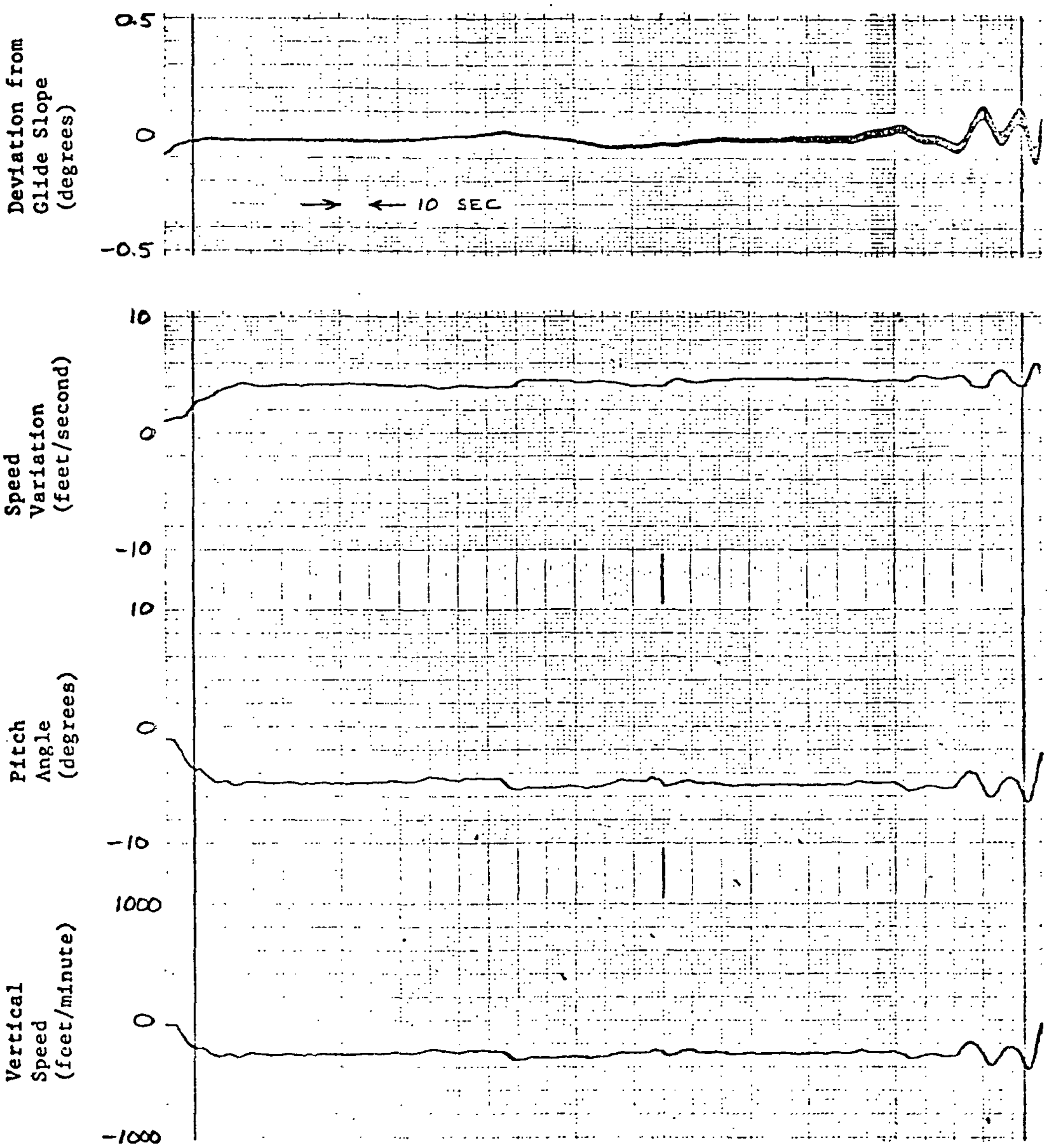


Figure 34

Conventional ILS Approach, Pilot G

5.2 Spoilers with Bang-Bang Position Controller

Pilots A, B, and D made ILS approaches using the bang-bang position spoilers for flight path control (refer to Section 2.1.3 for description). Generally, the procedure used was as follows. Before reaching the outer marker, the spoilers were deflected 20 degrees, the 50 % bias position. When the glide slope was intercepted a power reduction was made to achieve the reference descent rate. After that, spoilers were used as required to follow the glide slope, with the throttle remaining fixed.

Pilot A flew with several different spoiler pitching moments to evaluate general handling qualities. Figure 35 shows an approach with $M_{\delta_{sp}} = -.2165$ (-1/2 times nominal pitching moment). The three periods of spoiler activity seen correspond exactly with the periods of large pitching oscillation (10 degrees of pitch, 1200 fpm vertical speed change). The pilot's description was "horrendous pitch response... ...way too much pitch response," or in other words, decidedly unpleasant handling qualities. Figure 36 shows an approach with 0 spoiler pitching moment. Again, spoiler activity induced large amplitude phugoid motion. Pilot comment was "lots of pitch oscillation." As far as glide slope tracking goes, the approach was not too bad, with RMS error of .132 deg. Figure 37 shows an approach with nominal spoiler pitching moment ($M_{\delta_{sp}} = .433$). A much lower degree of pitching oscillation was present in spite of frequent spoiler control inputs. Glide slope tracking was fairly good (RMS error = .075 deg.) and well controlled. Pilot comments were "things more under control... ...I like not having to fool with the throttle." Note that almost

all of the spoiler inputs were in the same direction; this implies that the power was set slightly off (low). It is obvious that a fixed spoiler deflection between 0 and 20 degrees would have given the correct descent rate. An approach by Pilot A with constant C_L pitching moment and turbulence is shown in Figure 38. Like that of Figure 37, this approach was well controlled (RMS error = .069 deg.) and smooth. Pilot A had no great difficulty controlling flight path with spoilers when spoiler pitching moment was sufficiently positive, but 0 or negative pitching moment was unsatisfactory due to handling difficulties.

Pilot B, who had trouble making good conventional ILS approaches, had better luck when using spoilers. On his spoiler-controlled approaches, the aircraft didn't go outside the 1-degree-wide glide slope course as much as it did during some conventional approaches. An approach flown by Pilot B with constant C_L pitching moment is shown in Figure 39 (RMS error = .076 deg.). Note that again all spoiler inputs were in the same direction; the aircraft consistently tended to climb above the glide slope. Overall, Pilot B was pleased with the performance of the spoiler control system.

Pilot D liked the spoilers very much, feeling that he had "precise control." A typical approach by him is shown in Figure 40, where spoiler pitching moment was nominal. RMS error was .137 deg. A small amplitude phugoid motion was present, but the pilot was not bothered by it.

The bang-bang position command controller was shown to give sufficient control to follow the glideslope if the power setting

was reasonable. However, the smallest control input which could be made with this controller was 20 degrees, 50 % of the available authority. These large control inputs tended to excite the aircraft's phugoid mode, with the amplitude increasing as spoiler pitching moment changed in the negative direction. Because of this problem, it would seem better to have a controller which provides for infinite variation of spoiler position, so that small changes in position could be made.

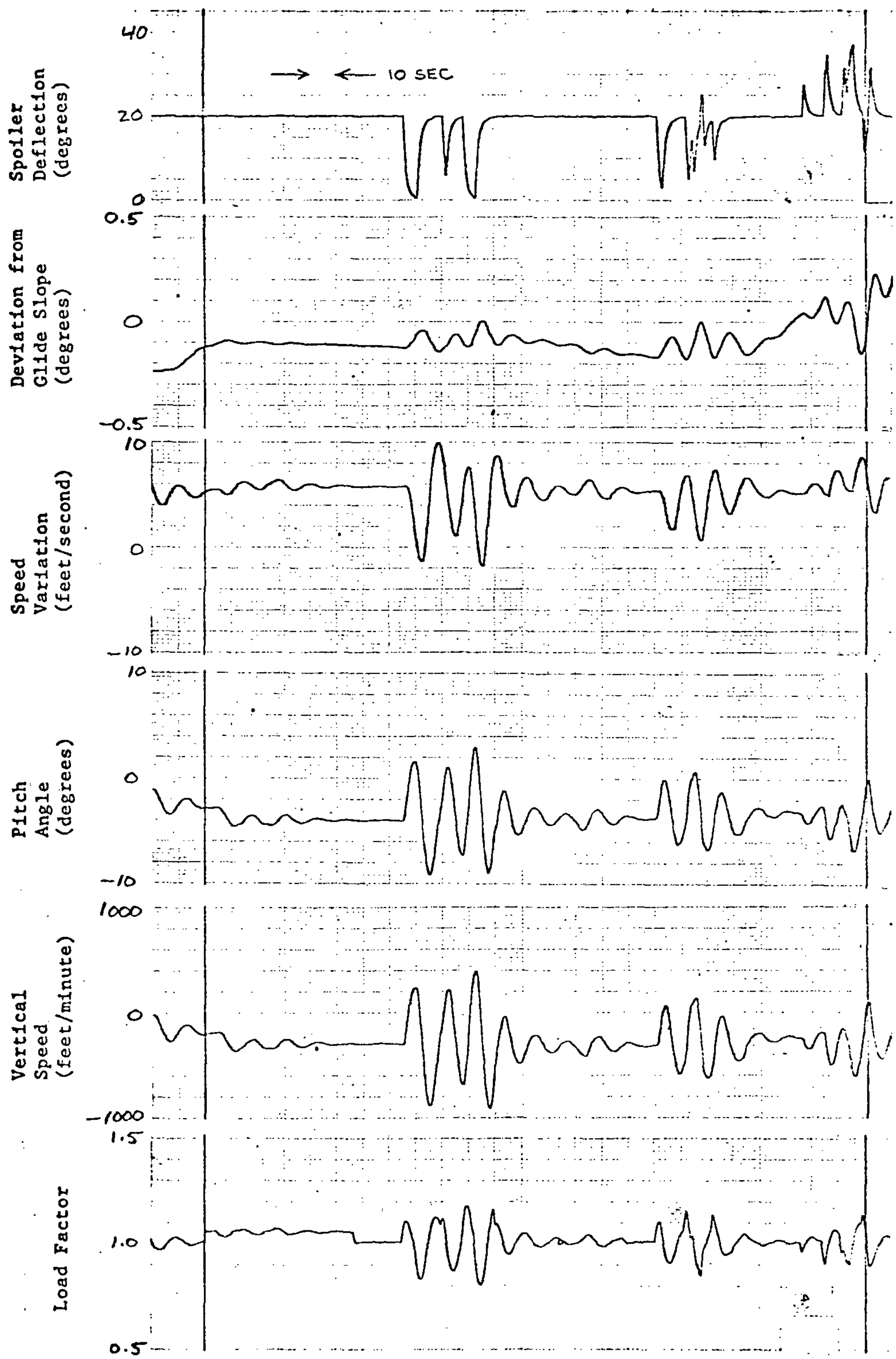


Figure 35

ILS Approach with Bang-Bang Position Spoilers

Pilot A

$M_{\delta_{sp}} = -.2165$

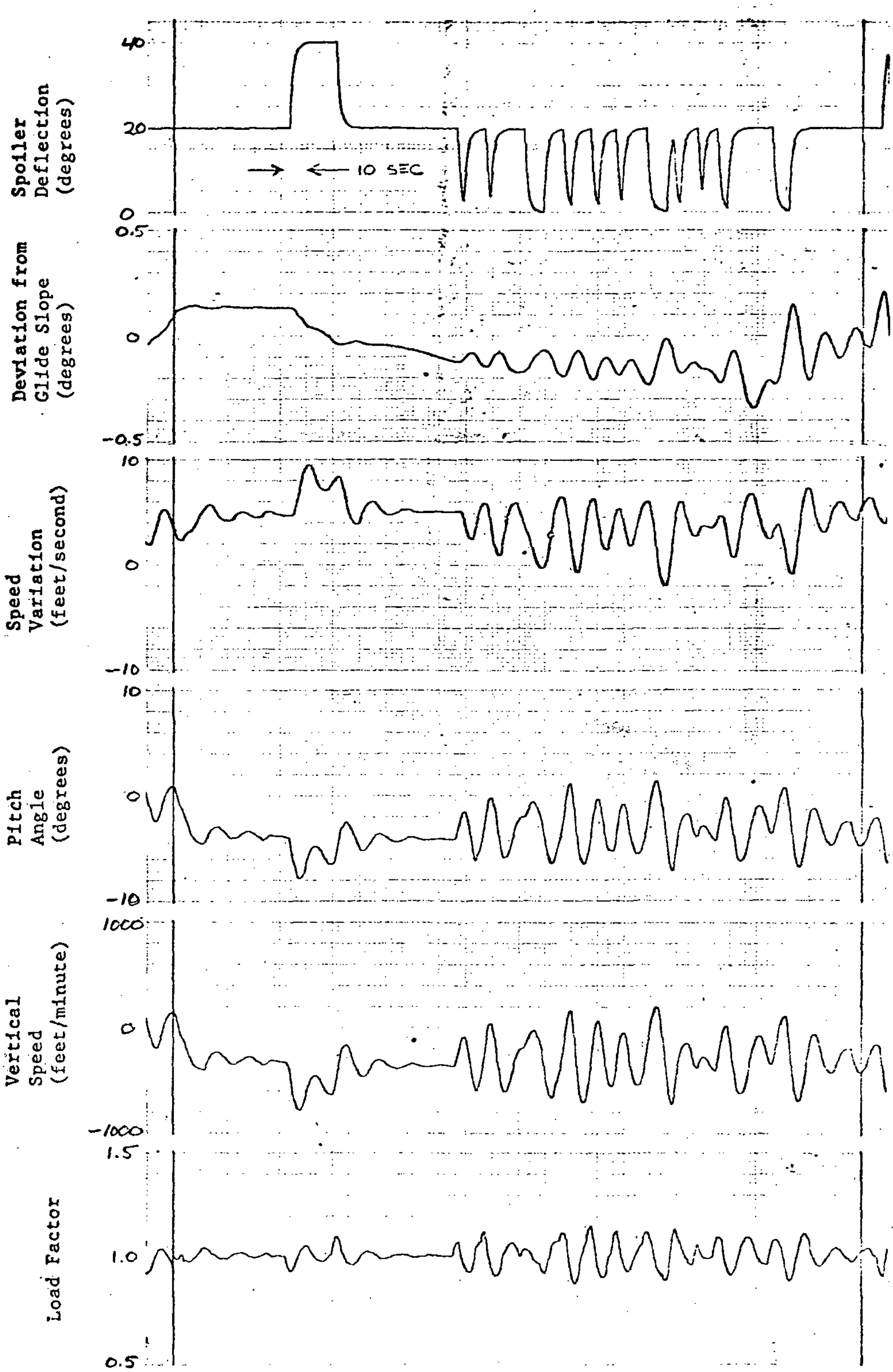


Figure 36

ILS Approach with Bang-Bang Position Spoilers

Pilot A

$M_{\delta_{SP}} = 0$

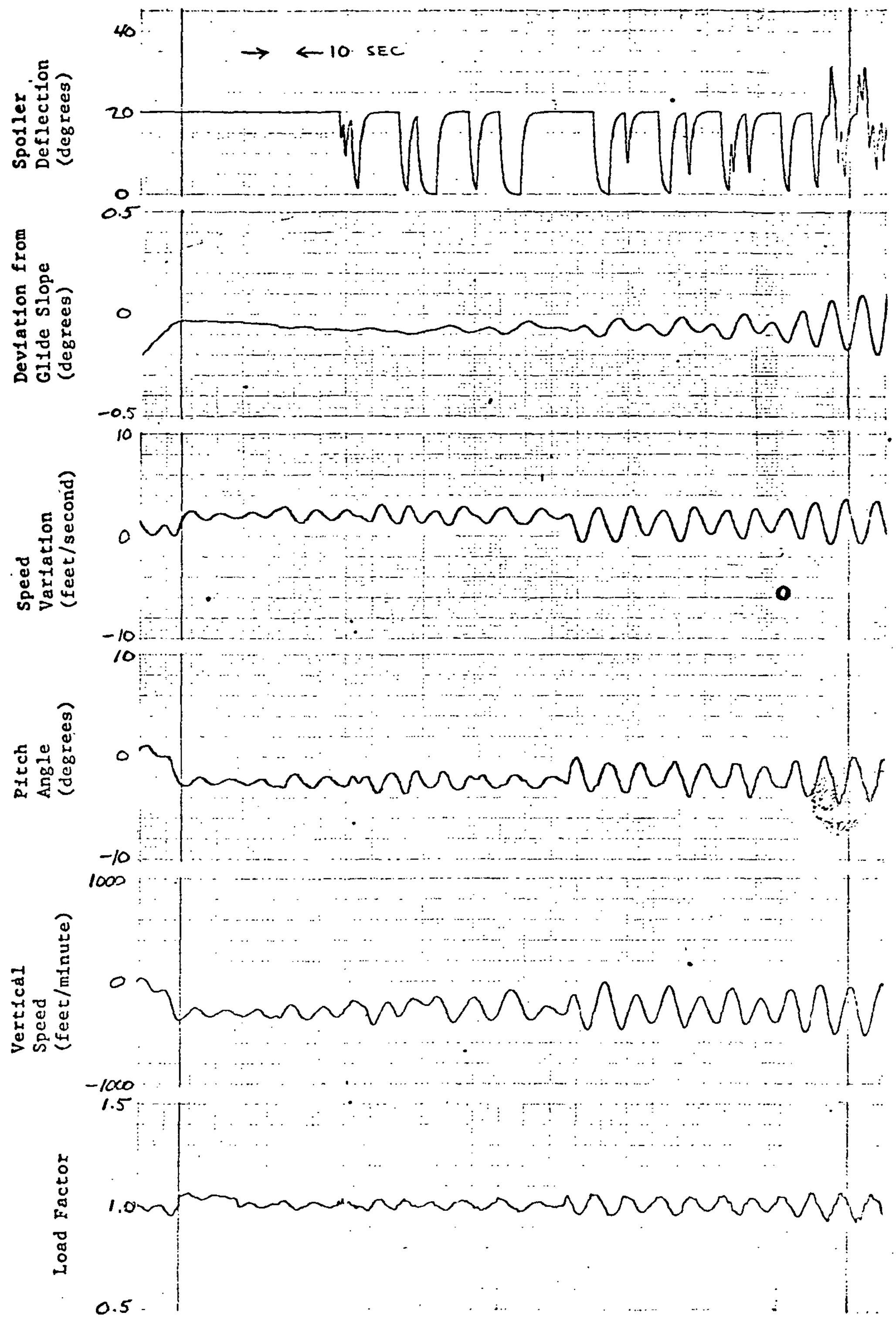


Figure 37

ILS Approach with Bang-Bang Position Spoilers

Pilot A

$M_{\delta_{sp}} = .433$

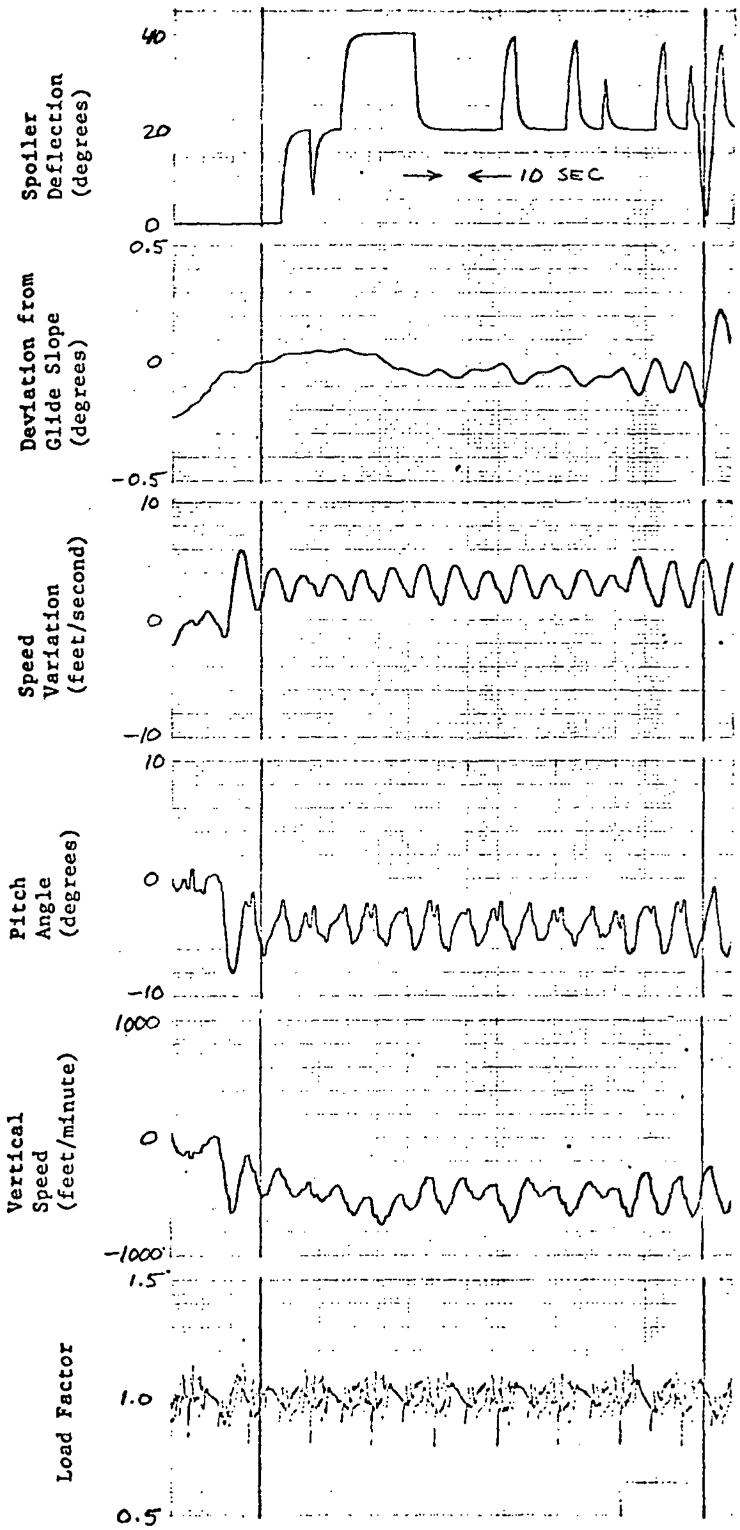


Figure 38

ILS Approach with Bang-Bang Position Spoilers

Pilot A

$M_{\delta_{SP}} = .471$

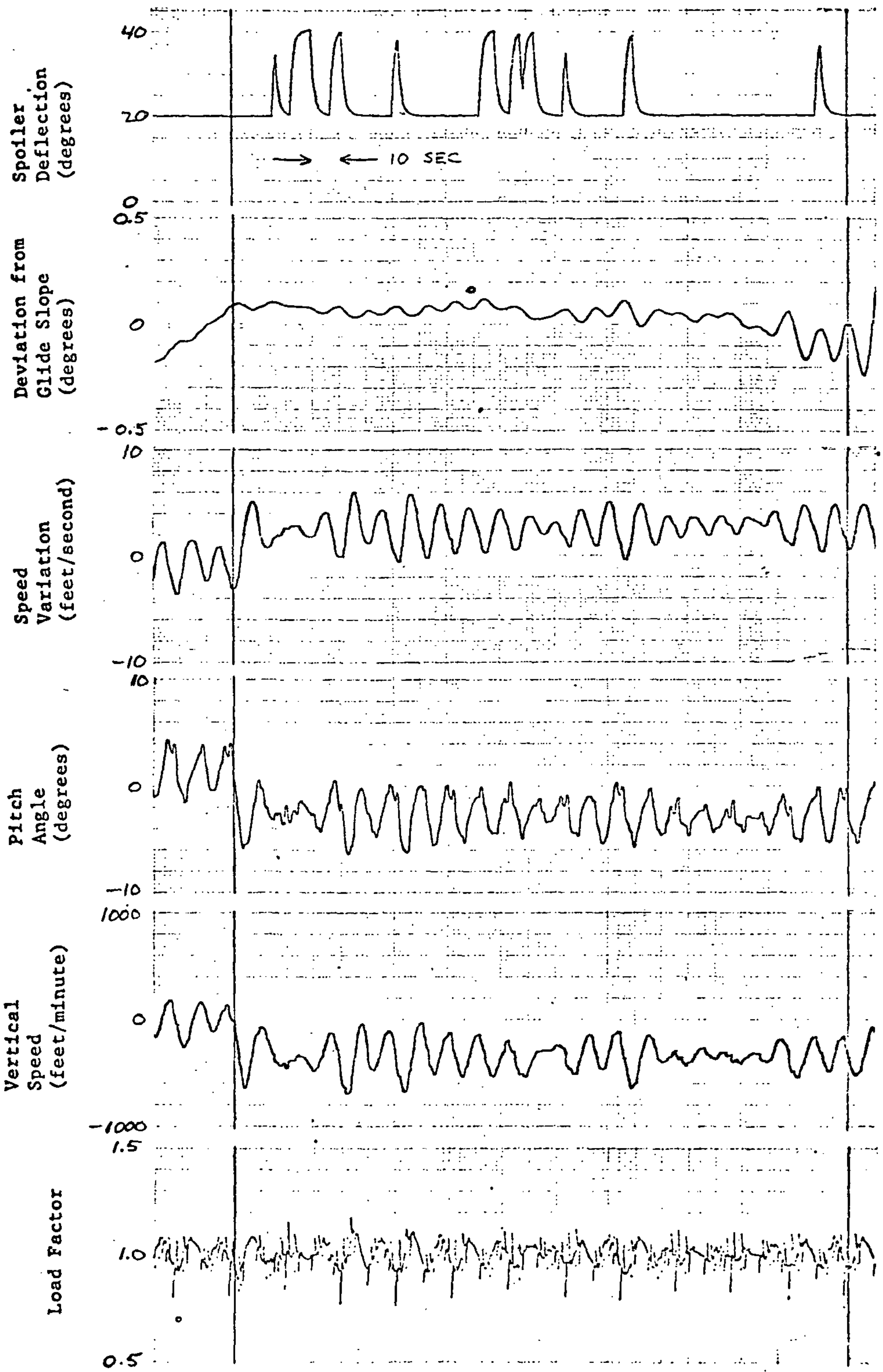


Figure 39

ILS Approach with Bang-Bang Position Spoilers

Pilot B

$M_{\delta_{sp}} = .471$

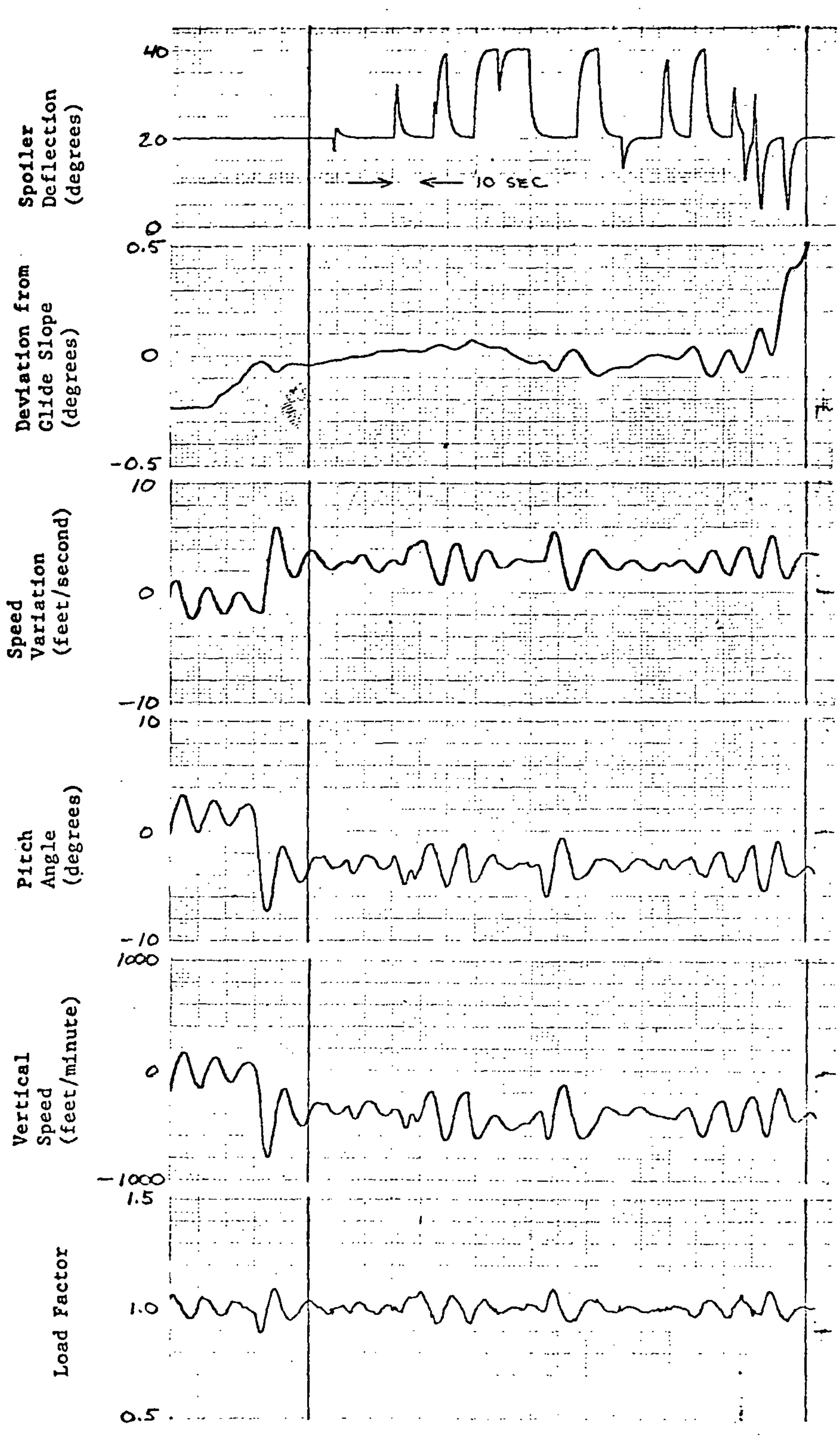


Figure 40

ILS Approach with Bang-Bang Position Spoilers

Pilot D

$M_{\delta_{sp}} = .433$

5.3 Spoilers with Thumbwheel Controller

The thumbwheel position command controller did provide for infinitely variable spoiler position. The approach procedure used was similar to that described above. At the outer marker, spoilers were to be deflected about 20 degrees by reference to the spoiler position indicator and a power reduction made to approximately match aircraft descent rate to the glide slope. For the rest of the approach the spoiler control was to be used as a descent rate control device to follow the glideslope.

The very first approach made by Pilot A using this controller is shown in Figure 41. The correlation between spoiler position and vertical speed/glideslope error can be clearly seen where the pilot used the spoilers to bracket the glide slope. Using about half of the spoiler authority available, the pilot moved up and down through the beam at will. The pilot's description of his control ability was "great." Note that speed and pitch attitude changes were practically nil even though longitudinal maneuvering was being done. Spoiler pitching moment in this example was nominal. This approach was typical for Pilot A, and he was very happy with this method of flight path control.

Pilot C also flew this spoiler controller and was quite satisfied with it. One of his typical approaches is shown in Figure 42. Glide slope tracking was good, and again, speed and pitch angle variations were negligible. Note that the pilot tended to seek and converge on the spoiler setting which would give the proper steady-state descent rate, 5 - 10 degrees in this case. The pilot felt he had

very precise control over flight path. His only complaint concerned the sensitivity of the thumbwheel, which required a fine touch to make small changes in spoiler position. He felt that this would be difficult in a real plane in turbulence, but a less sensitive wheel with more friction would probably work all right.

Figure 43 shows an approach in turbulence by Pilot E. Like the others, he liked the spoiler system and had no difficulty making good approaches like the one shown using the system. Figure 44 shows an approach by Pilot G in which he did some experimenting with the spoilers instead of trying to fly an accurate approach. Through the first part of the approach too much power was being carried, so that even with full spoilers (point A on the spoiler trace) the aircraft was still rising away from the glide slope. At that point, a small power reduction was made. Note the jump in trim speed just beyond point A. The pilot next made large changes in spoiler deflection to demonstrate the maneuvering authority available. He moved up and down with respect to the glide slope in response to spoiler commands, and finally crossed the middle marker on the glide path. This approach demonstrated that the spoilers gave adequate control for glide slope tracking with minimal speed and attitude disturbance, and showed the need for a correct initial power setting.

When making these approaches, the pilots had to add the spoiler position indicator to their instrument scans whenever spoiler position was being changed. This didn't seem to be any more distracting to the pilots than the attention normally given to the tachometer and

throttle when making a power change. None of the pilots indicated that having one more instrument to watch made any appreciable difference in his work load, since through most of the approach the engine controls and instruments could be paid less attention than they would normally. The need to monitor the spoiler position indicator could possibly be reduced by providing detents in the thumbwheel motion, perhaps every 2 degrees of spoiler travel. This would allow small adjustments to be made to spoiler position without the pilot looking at the position indicator to monitor the change being made.

In general, the evaluation pilots were quite enthusiastic about the thumbwheel spoiler system. They felt that it was far superior to the bang-bang position system because of the precise control available and the absence of any spoiler-induced pitching motion (when using nominal or constant C_L spoiler pitching moment). All agreed that these spoiler-controlled approaches were less demanding to fly than conventional ILS approaches.

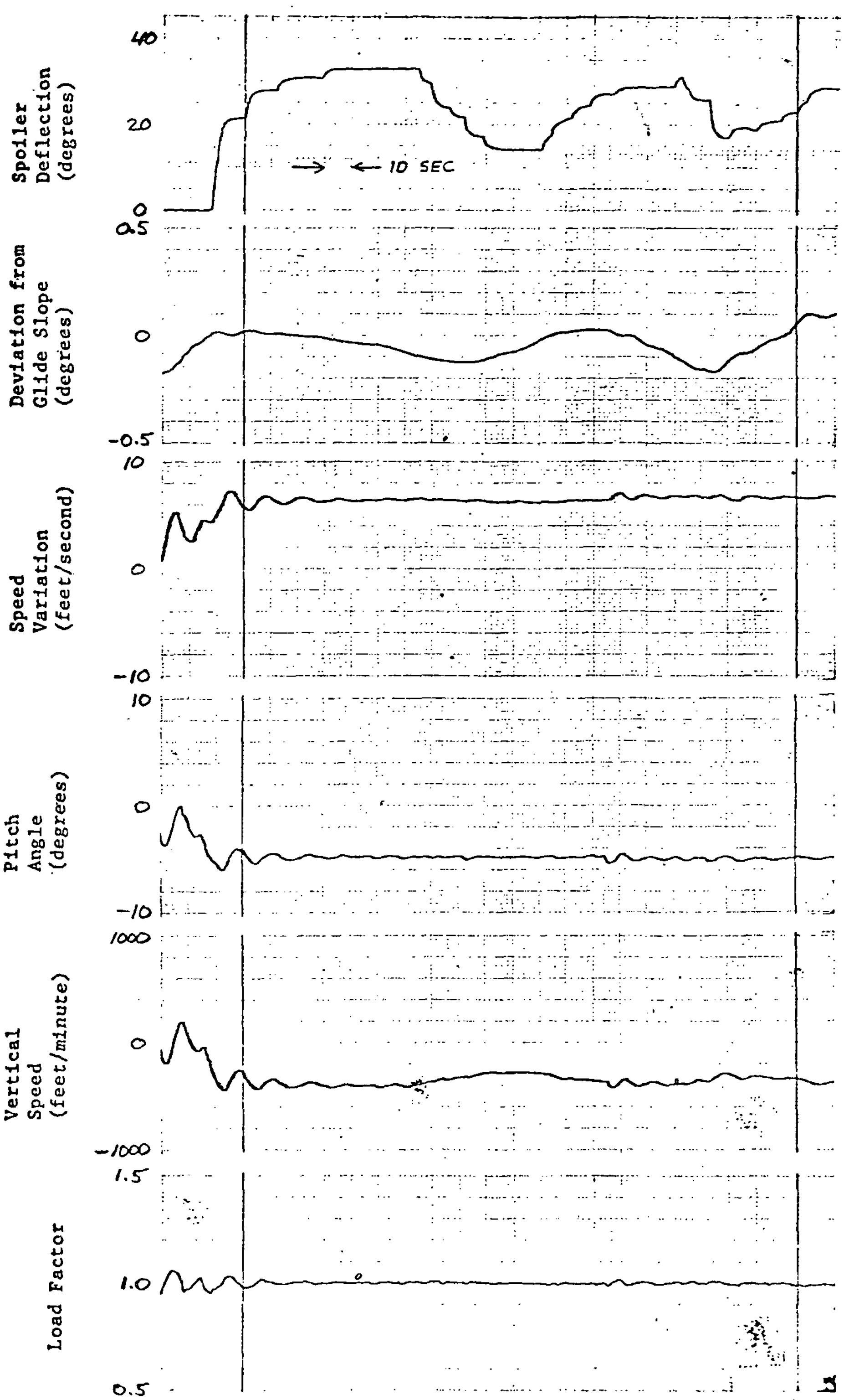


Figure 41

ILS Approach with Thumbwheel Spoiler Control

Pilot A

$M_{\delta_{sp}} = .433$

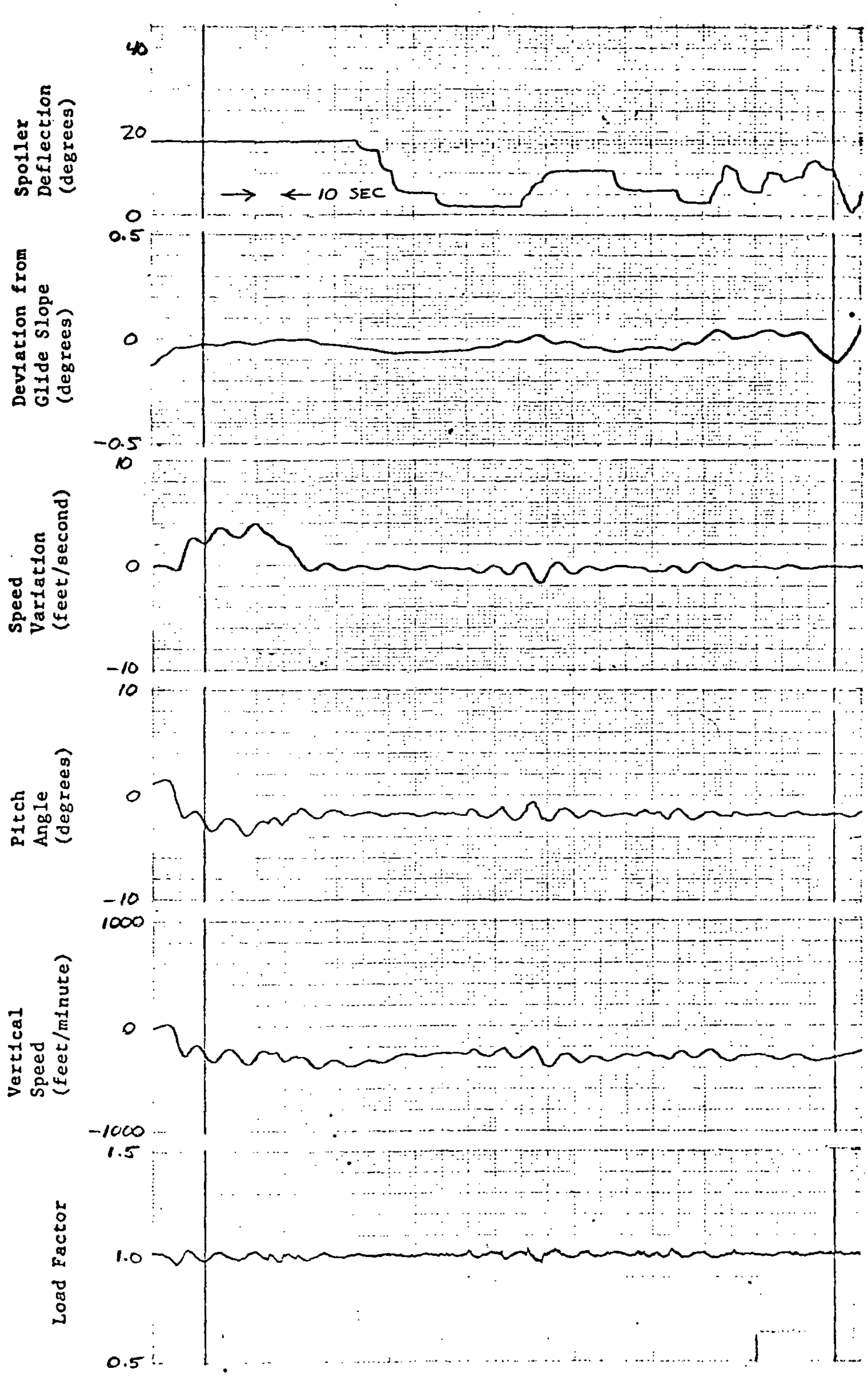


Figure 42

ILS Approach with Thumbwheel Spoiler Control

Pilot C

$M_{\delta_{sp}} = .471$

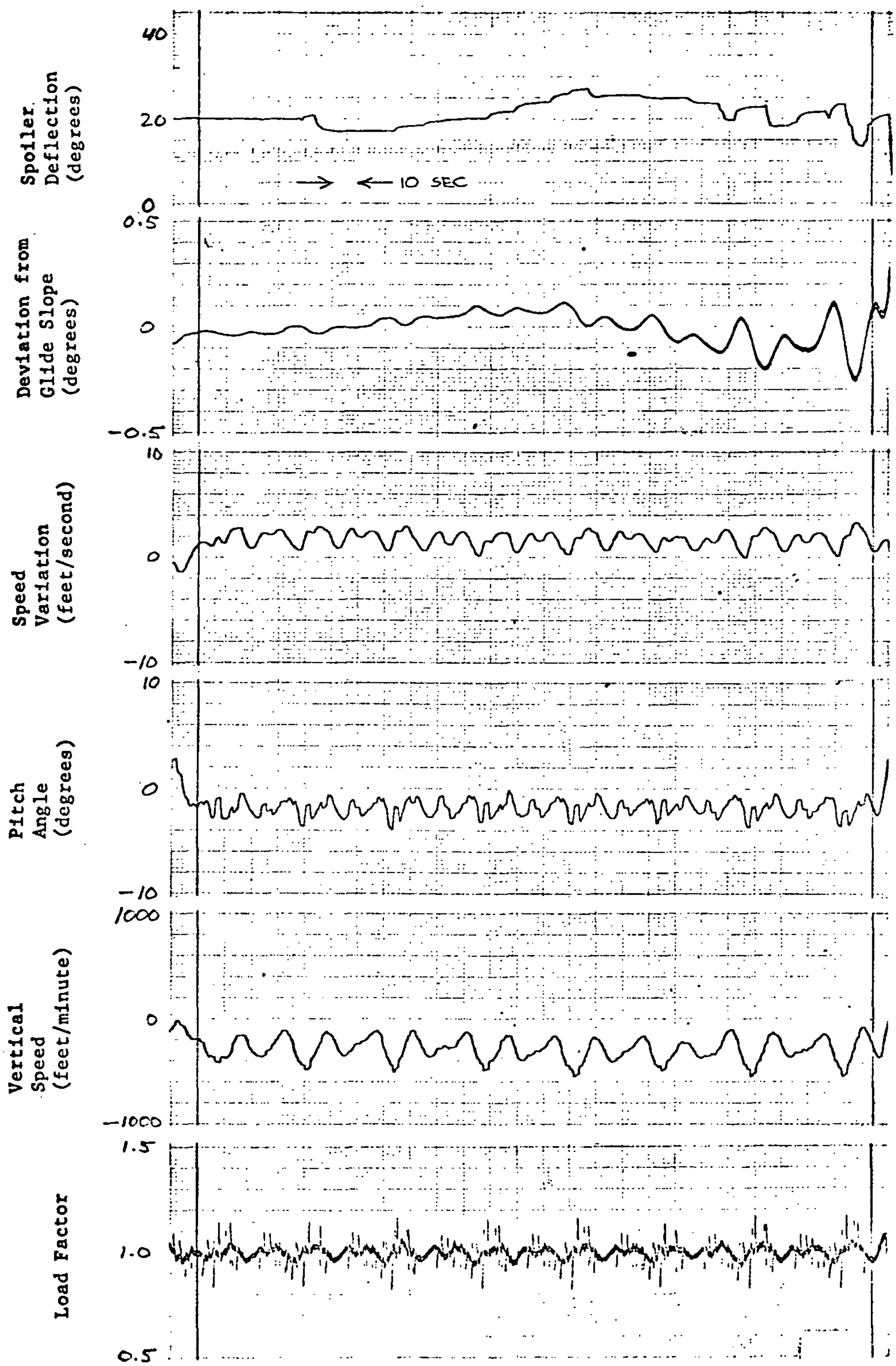


Figure 43

ILS Approach with Thumbwheel Spoiler Control

Pilot E

$M_{\delta_{sp}} = .471$

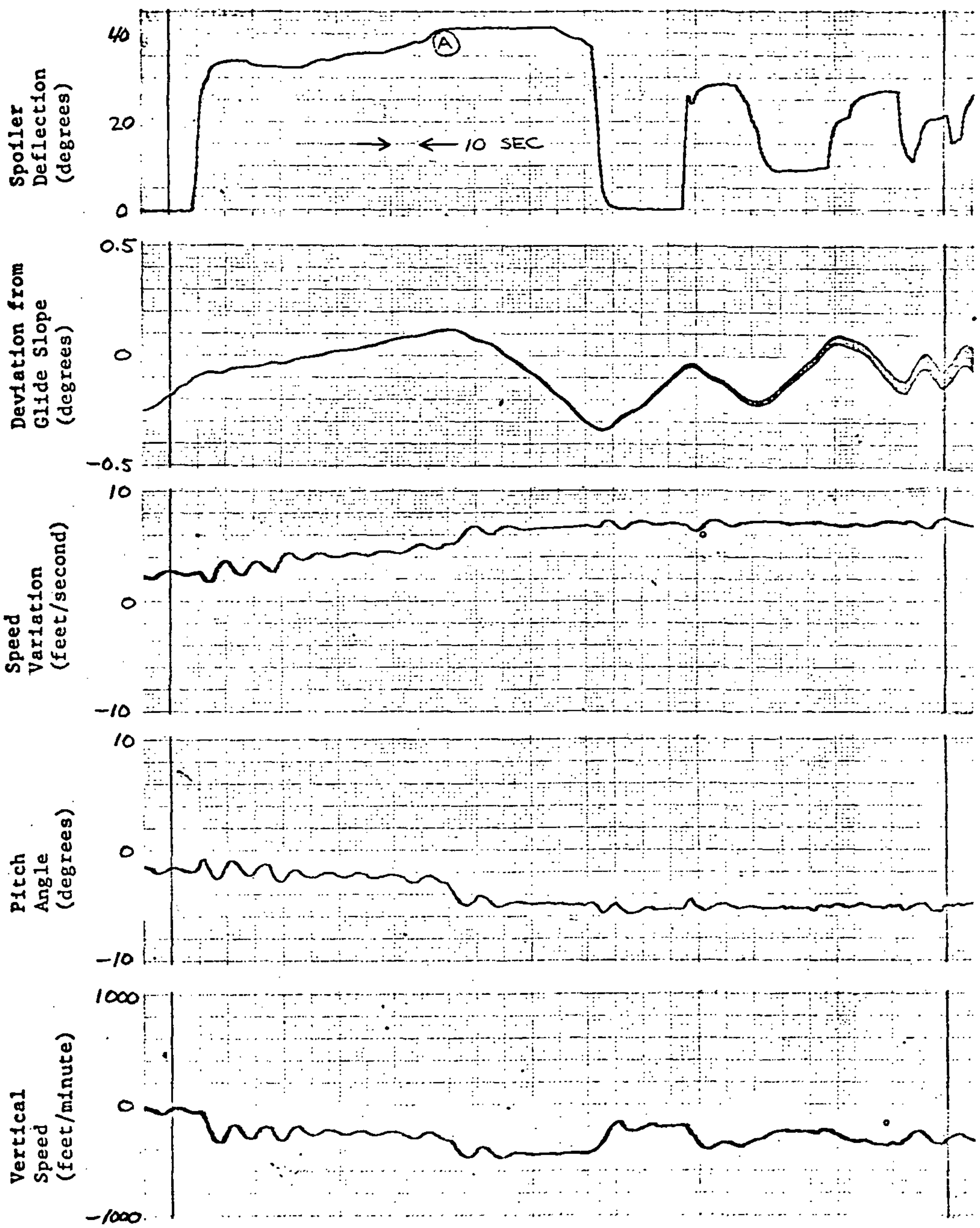


Figure 44

ILS Approach with Thumbwheel Spoiler Control

Pilot G

$M_{\delta_{sp}} = .471$

5.4 Spoilers with Bang-Bang Rate Controller

The bang-bang rate spoiler controller (Section 2.1.3), like the thumbwheel controller, provided for infinite variation of spoiler position. The six pilots who evaluated this controller were told to think of it as a descent rate trim control, since it was quite similar to a conventional electric pitch trim control. Approach procedures were the same as for the thumbwheel controller. All of these approaches were flown with the spoiler pitching moment giving constant C_L, since that moment had the best potential for good handling qualities.

An approach by Pilot A is shown in Figure 45. Using the spoilers, the pilot bracketed the glide slope a couple of times "homing in" on the spoiler setting which would give the proper steady descent rate. When he had found that setting (about 16 or 17 degrees), his spoiler corrections became smaller and less frequent, and he stayed right on the glide path from then on. Phugoid excitation was minimal, and the approach was smooth all the way.

Pilot B used a slightly different technique, as seen in Figure 46. His spoiler inputs were larger and less frequent than Pilot A's were. The glide slope was bracketed all the way down, but the pilot did not converge on a steady descent as Pilot A did. The approach shown was successful, though, since the aircraft did stay near the glide slope at all times. Because the phugoid motion continued even when no spoiler inputs were being made, it is assumed that the pilot was also moving the control wheel (longitudinally). The approach

might have been smoother had the pilot used only spoilers for longitudinal control, as intended.

Pilot C (Figure 47) and Pilot F (Figure 48) made smooth, accurate approaches with this spoiler system. Note that both pilots made relatively small spoiler corrections because their initial power settings were close to optimum. This once again shows the importance of proper power management. By taking the trouble to accurately set the descent power setting at the outer marker, a pilot can make the rest of the approach relatively simple.

An approach by Pilot G in turbulence is shown in Figure 49. This also was a good approach. As the turbulence-induced phugoid motion began to appear on the glide slope indicator, the pilot attempted to fight it with the spoilers. This can be clearly seen toward the end of the approach. It looked like several of the other pilots also tried to do the same thing throughout the investigation. However, none of them had any success at damping this oscillation. Since the effective gain of the glide slope indicator is rapidly increasing at low altitudes, attempts to chase the needle led to a diverging pilot-induced oscillation (PIO).

This controller, like the thumbwheel controller, required occasional reference to the spoiler position indicator, but to a lesser degree. With a little practice, most of the evaluation pilots learned to make short "blips" of the control switch like they might use with a trim switch. This gave some feel for the magnitude of the deflection being made without actually watching the position

indicator. Pilot G even commented that he naturally started counting how many blips he made in each direction to keep track of the deflection he was commanding. Of course, an occasional glance at the indicator was necessary to know how much of the available control authority was being used.

All of the pilots who tried it praised this method of flight path control, considering it effective and easy to use. There wasn't any strong preference among them for this controller over the thumbwheel, or vice versa. Several pilots liked one a little better than the other, but couldn't give any solid basis for their preference. Since both controllers actually accomplish the same thing, infinitely variable spoiler position, any choice is mostly a matter of personal preference or practical considerations.

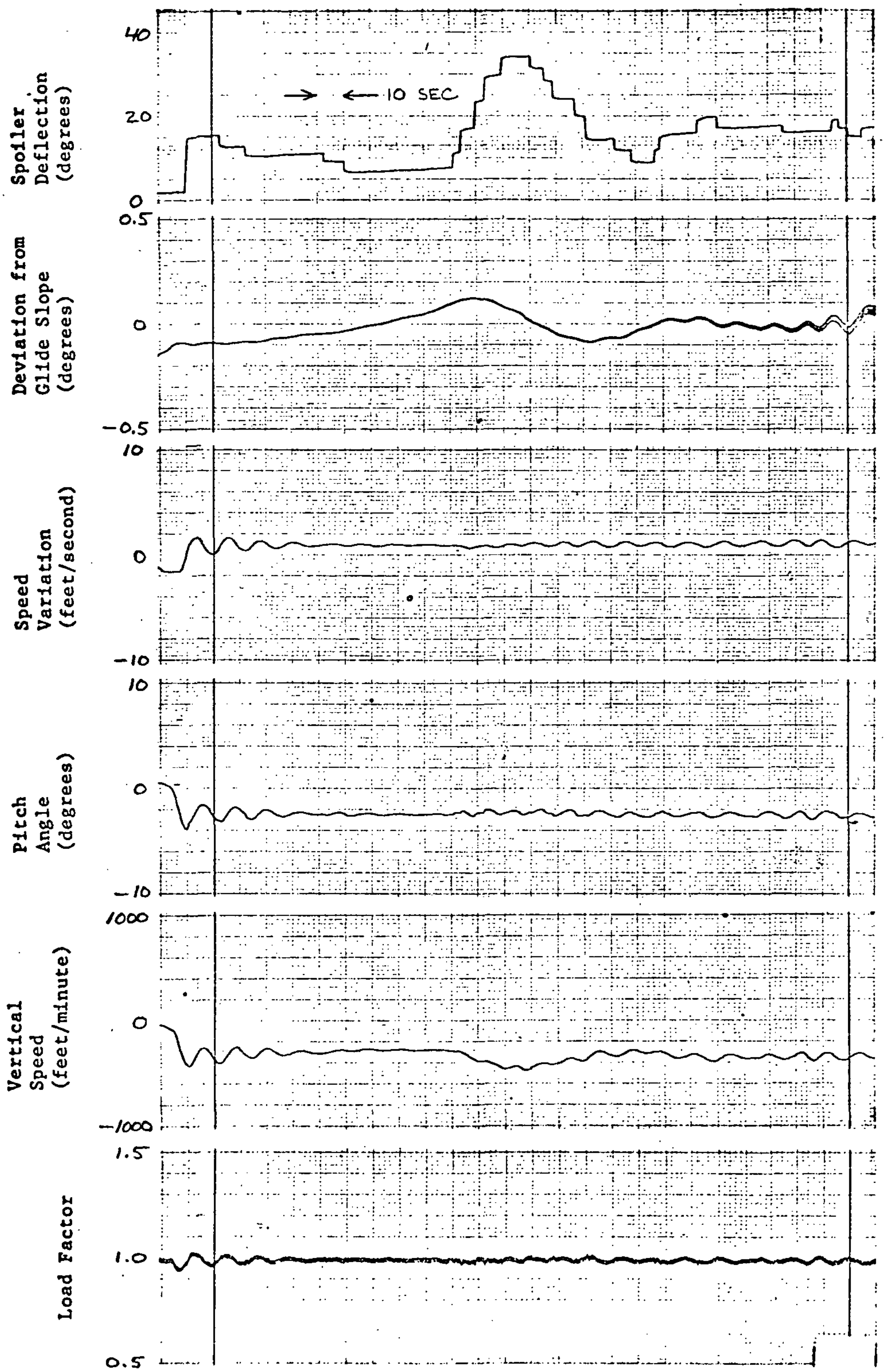


Figure 45

ILS Approach with Bang-Bang Rate Spoiler Control

Pilot A

$M_{\delta_{SP}} = .471$

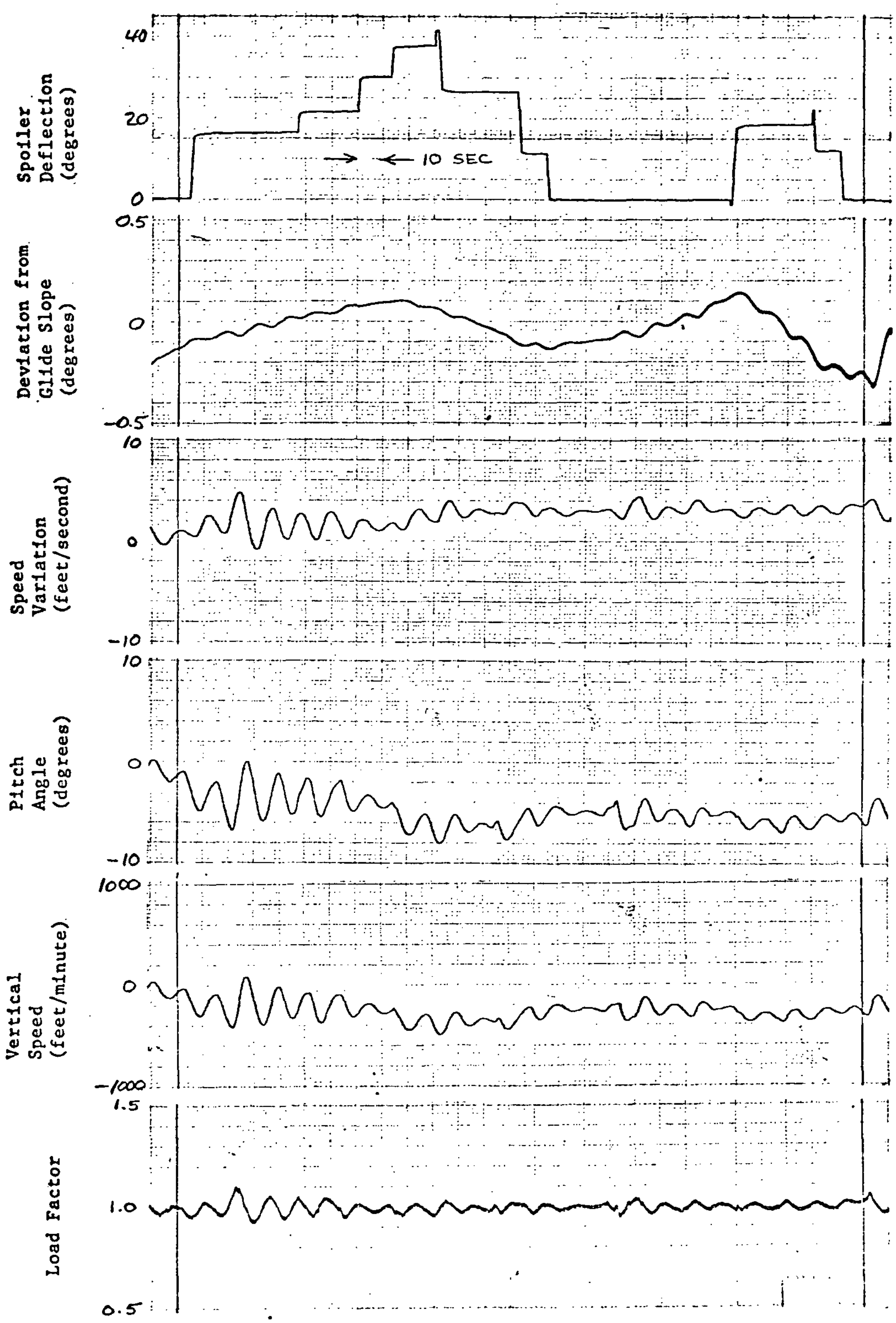


Figure 46

ILS Approach with Bang-Bang Rate Spoiler Control

Pilot B

$M_{\delta_{sp}} = .471$

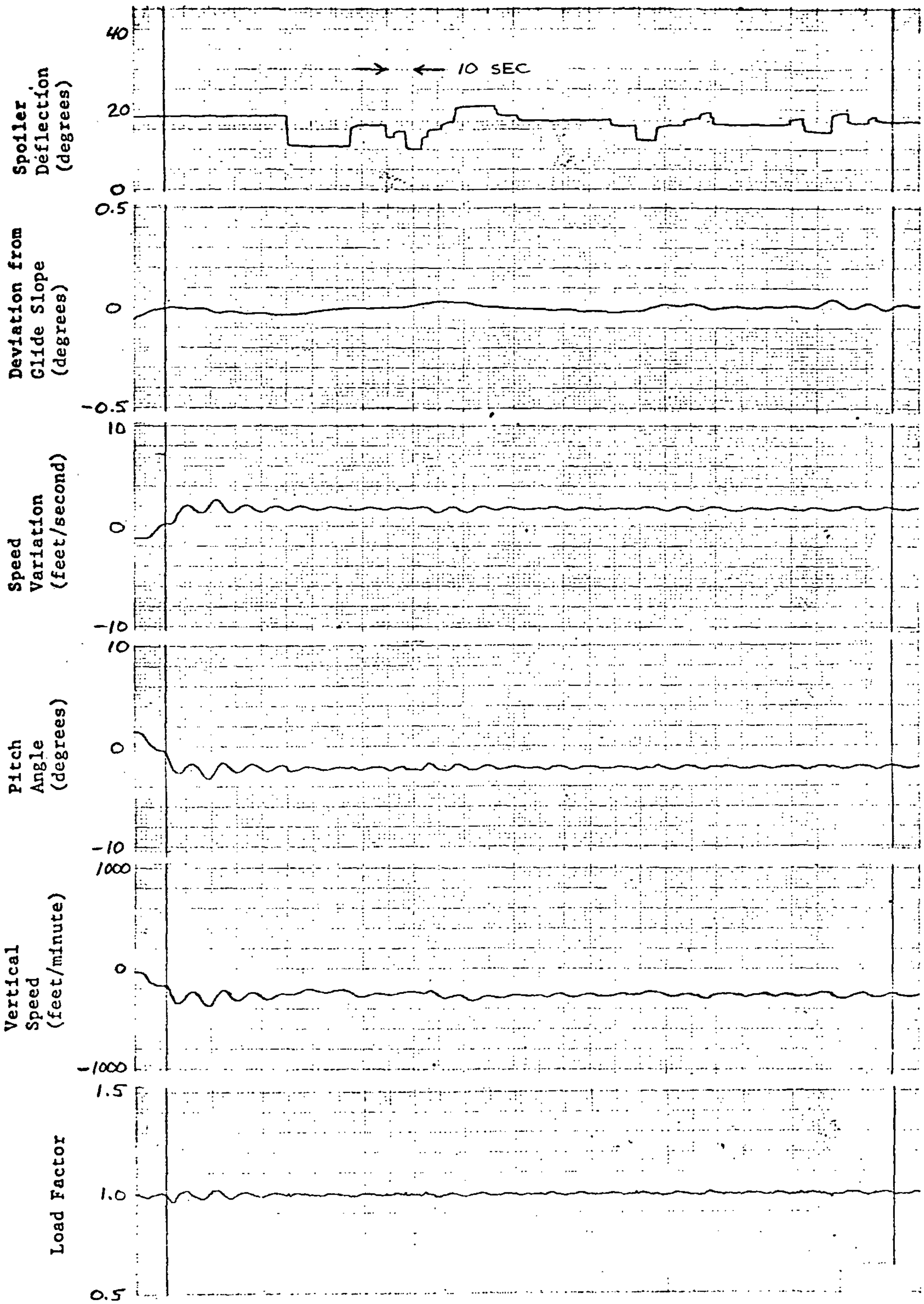


Figure 47

ILS Approach with Bang-Bang Rate Spoiler Control

Pilot C

$M_{\delta_{sp}} = .471$

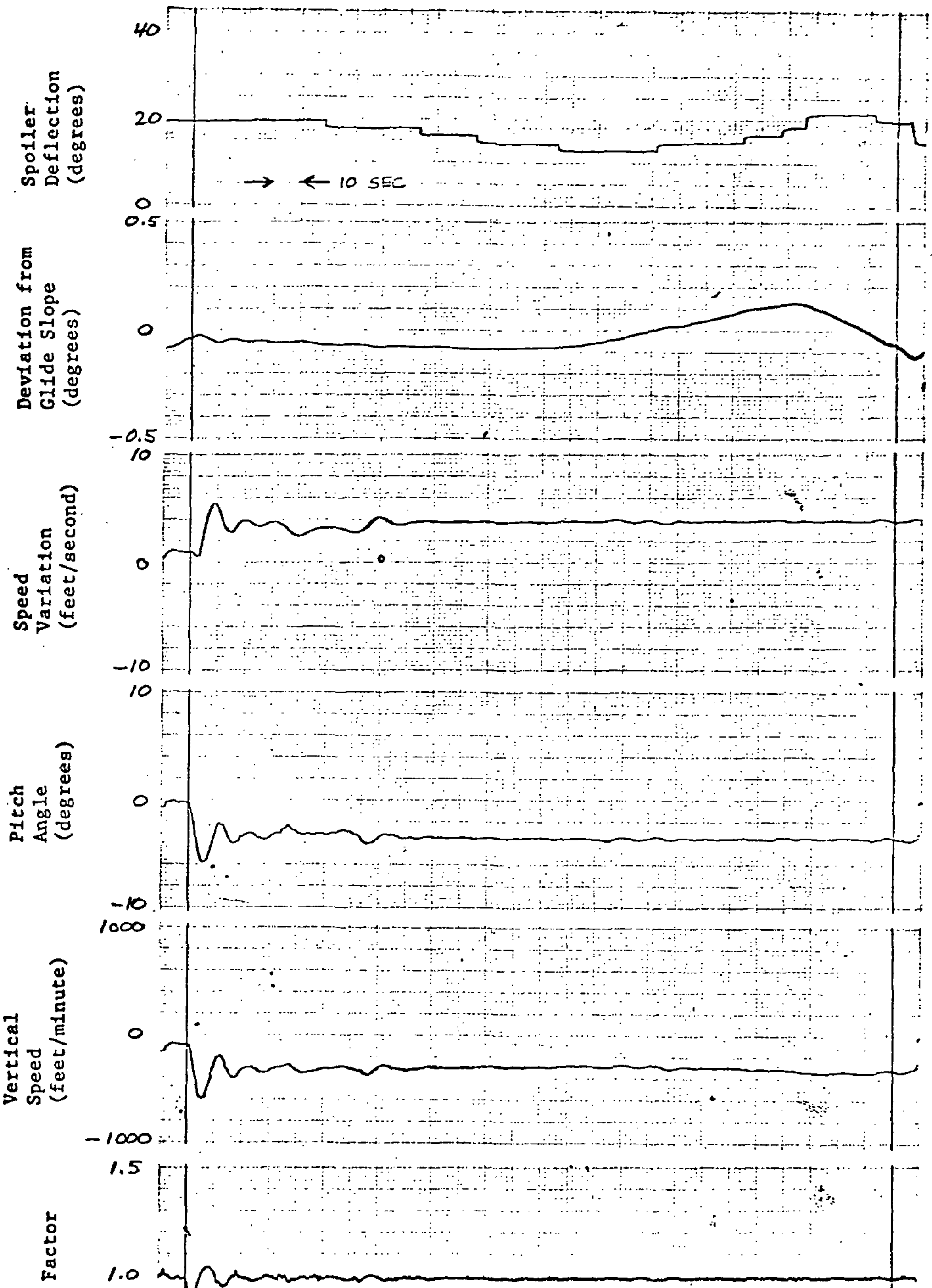


Figure 48.

ILS Approach with Bang-Bang Rate Spoiler Control

Pilot F

$M_{\delta_{SP}} = .471$

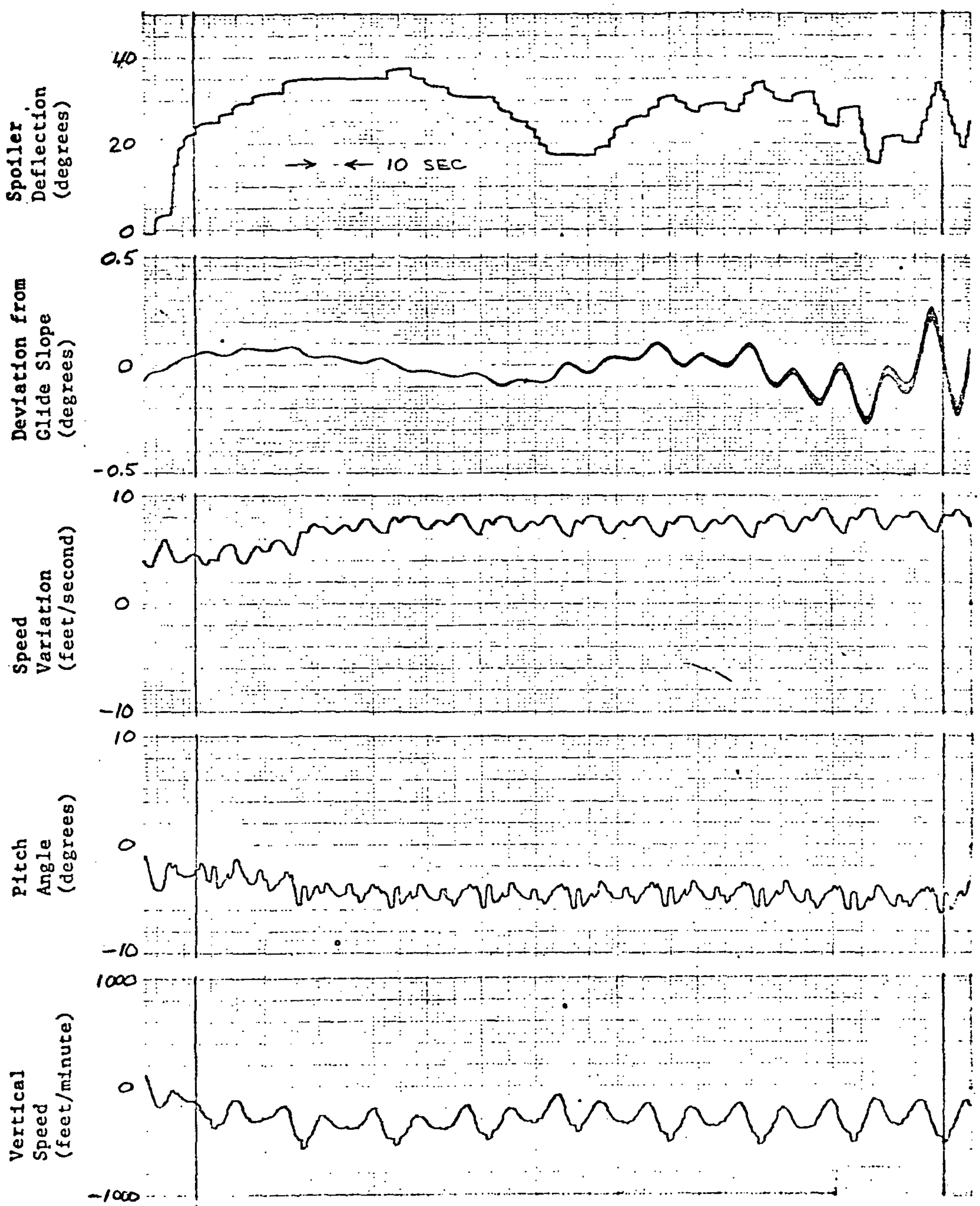


Figure 49

ILS Approach with Bang-Bang Rate Spoiler Control

With Turbulence

Pilot G

$M_{\delta_{sp}} = .471$

5.5 Summary of ILS Performance

The instrument rated pilots (D,F, and G) felt that the simulation of the ILS approach situation was realistic. The judgement of Pilot G was especially valued because of his wide flying experience and the fact that he had flown a number of sophisticated airline simulators. He felt that the realism of this simulation was quite adequate for the use intended. Pilots not used to the simulator were sometimes bothered by a small deadband in the lateral control forces, but this was not considered significant.

The performance of each pilot using the various methods of control discussed above is shown in Figures 50 - 56. These figures show the RMS glide slope error for the approaches flown by each pilot. There was generally no dramatic increase in approach accuracy using the spoilers for control, but several pilots (B, D, and F) seemed to make more consistent approaches with them compared to their conventional approaches.

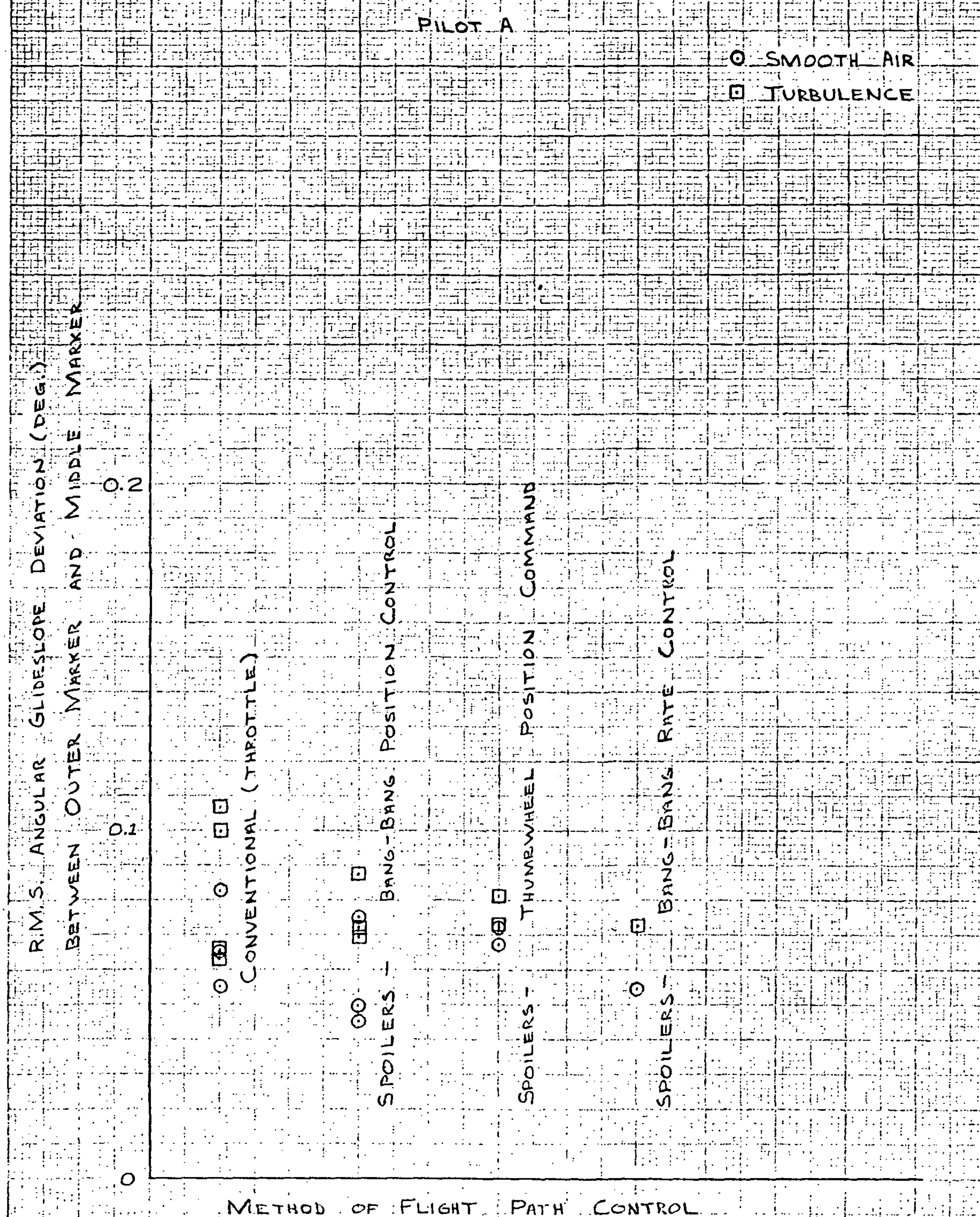
As a general rule, the approaches with RMS error of 0.1 degree or less would be considered very good, and 0.2 degree or less would usually be satisfactory. Figure 57 shows all approaches by all the pilots except those with zero or negative spoiler pitching moment. Seven approaches had RMS error greater than 0.2 degree, and five of those were conventional. In all seven approaches, the problem was caused by power mismanagement. When the power was adjusted properly, the pilots felt that it was easy to use the spoilers to fly a satisfactory approach. While some very accurate approaches were flown conventionally, the pilots generally agreed that the level of difficulty,

and thus pilot workload, was lower with the spoiler flight path control system.

FIGURE 50

PILOT PERFORMANCE OF THE

ILS APPROACH TASK



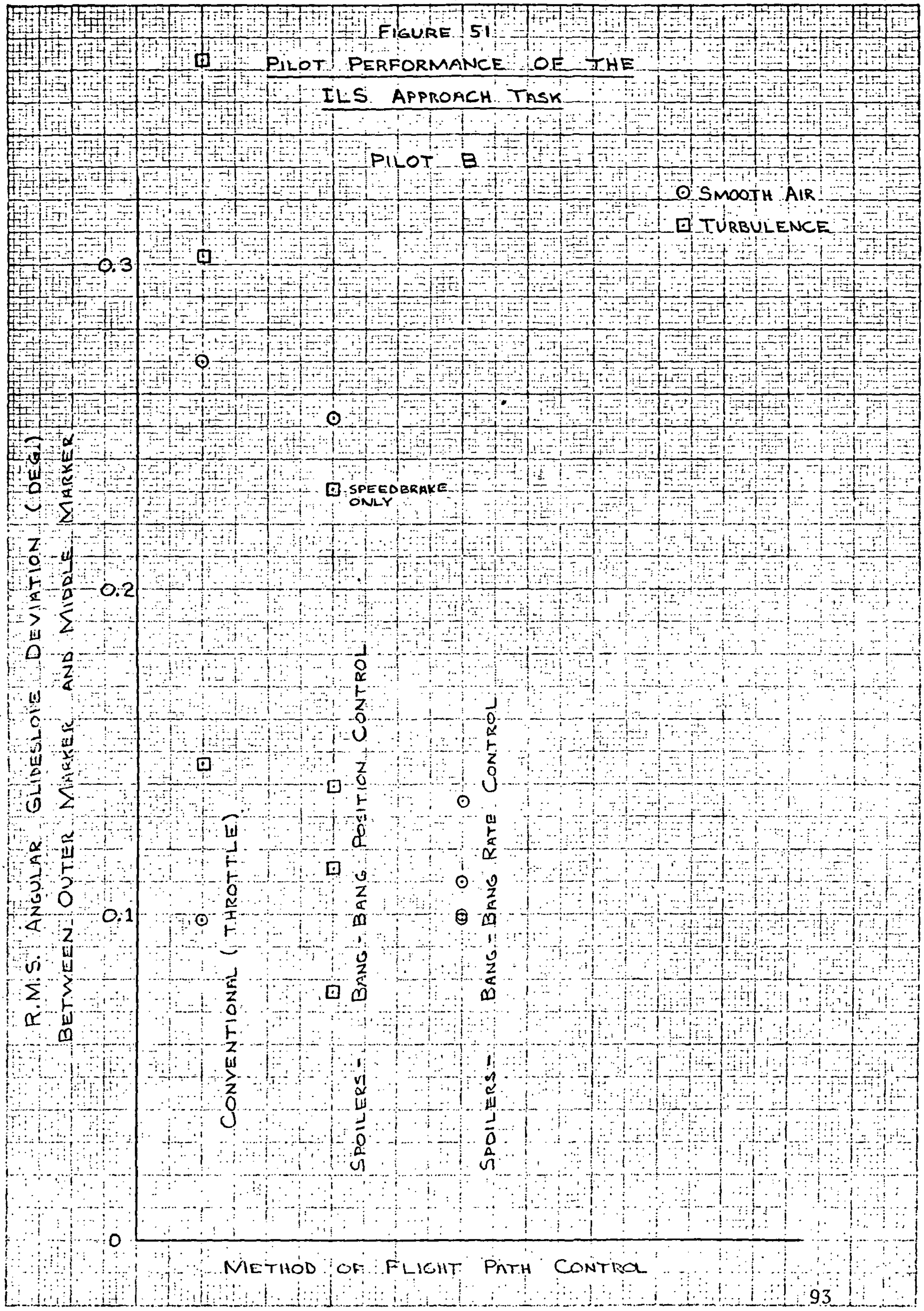


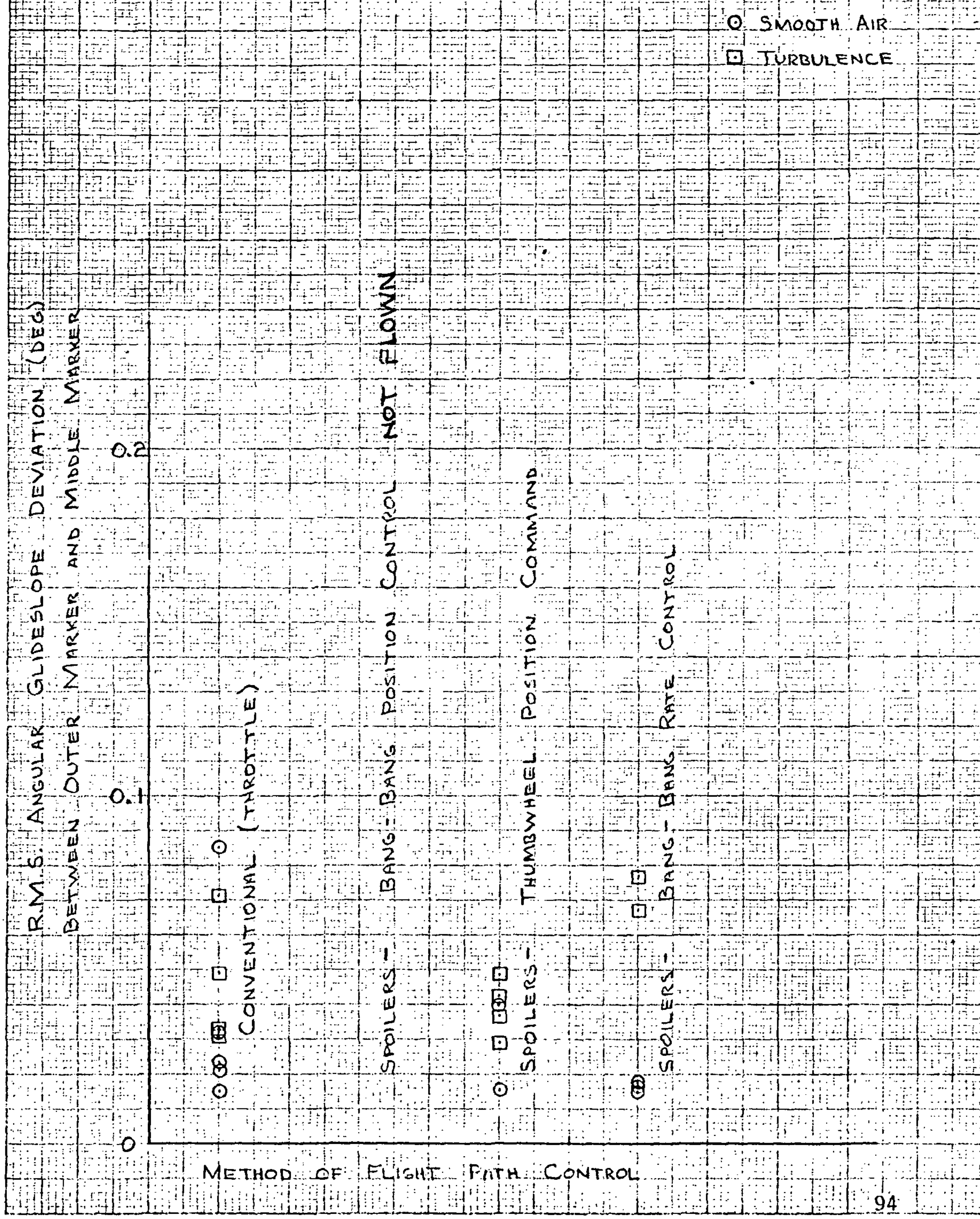
FIGURE 51
PILOT PERFORMANCE OF THE
ILS APPROACH TASK
PILOT B
SMOOTH AIR
TURBULENCE
SPEEDBRAKE ONLY
R.M.S. ANGULAR GLIDESLOPE DEVIATION (DEG.)
BETWEEN OUTER MARKER AND MIDDLE MARKER
0.3
0.2
0.1
0
CONVENTIONAL (THROTTLE)
SPOILERS - BANG - BANG POSITION CONTROL
SPOILERS - BANG - BANG RATE CONTROL
METHOD OF FLIGHT PATH CONTROL

FIGURE 52

PILOT PERFORMANCE OF THE

ILS APPROACH TASK

PILOT C



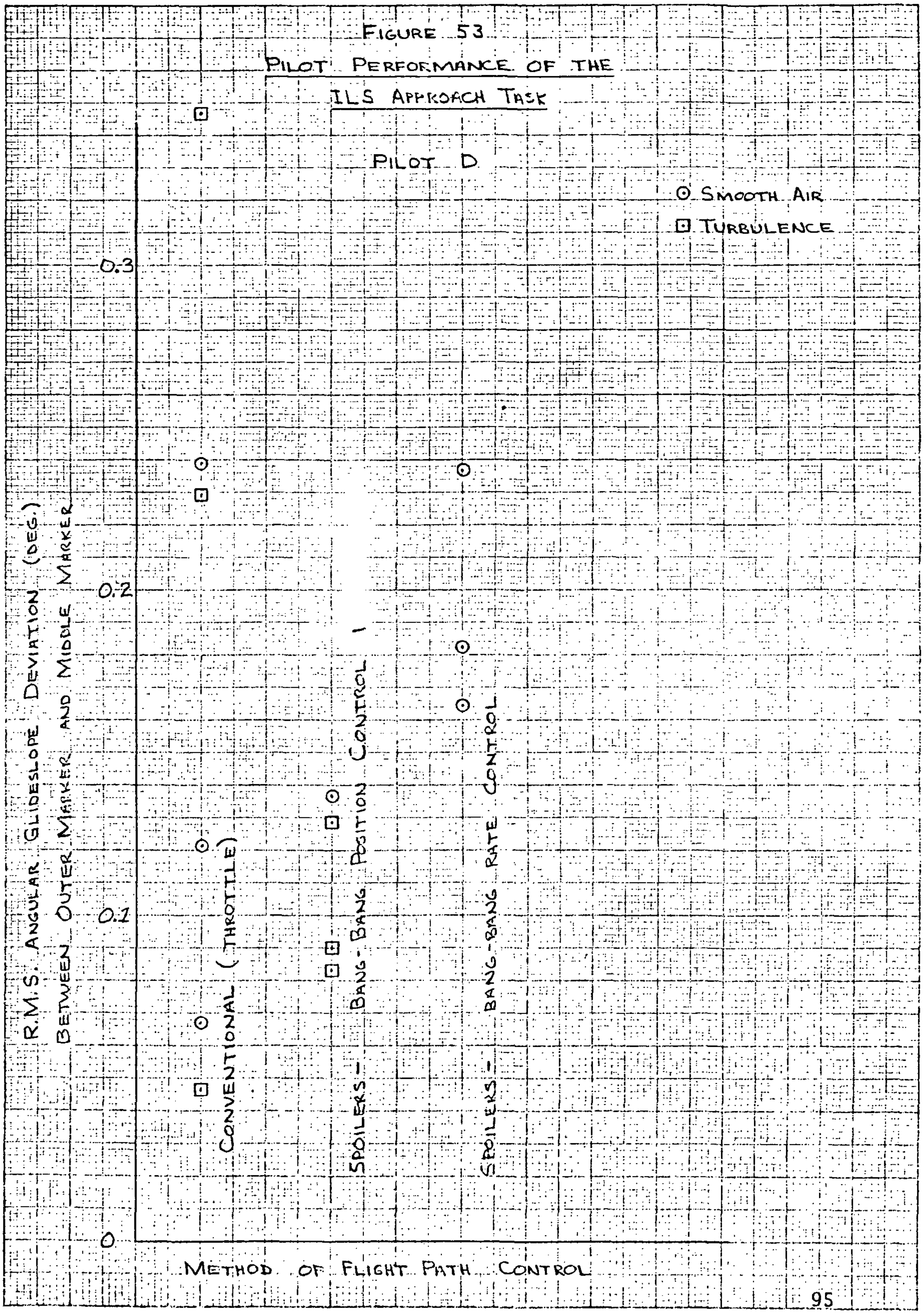


FIGURE 53
PILOT PERFORMANCE OF THE
ILS APPROACH TASK
PILOT D
⊙ SMOOTH AIR
⊡ TURBULENCE
R.M.S. ANGULAR GLIDESLOPE DEVIATION (DEG.)
BETWEEN OUTER MARKER AND MIDDLE MARKER
0.3
0.2
0.1
0
CONVENTIONAL (THROTTLE)
SPOILERS - BANG-BANG POSITION CONTROL
SPOILERS - BANG-BANG RATE CONTROL
METHOD OF FLIGHT PATH CONTROL

Figure 54

Pilot Performance of the

ILS Approach Task

Pilot E

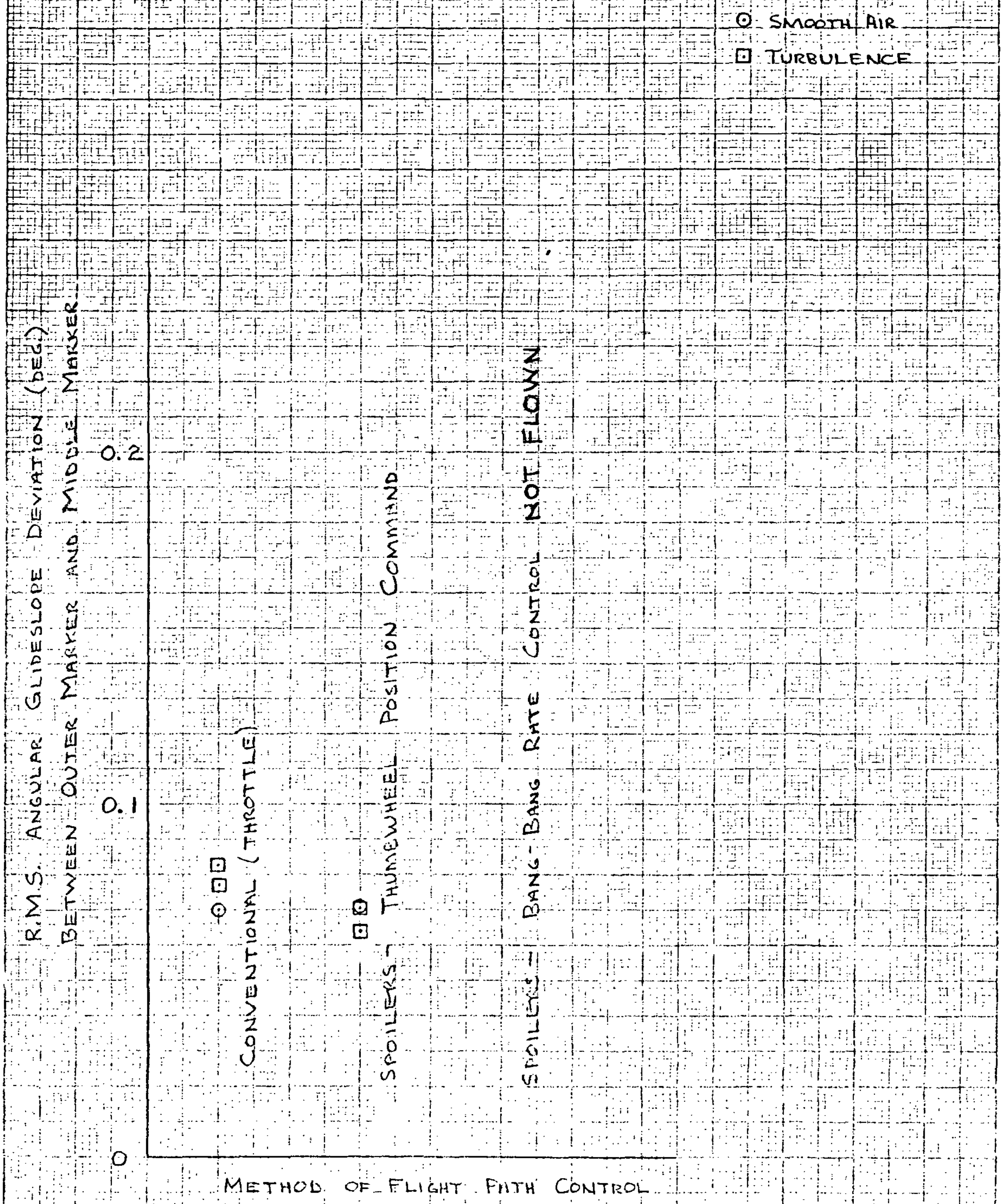


FIGURE 55

PILOT PERFORMANCE OF THE ILS APPROACH TASK

PILOT F

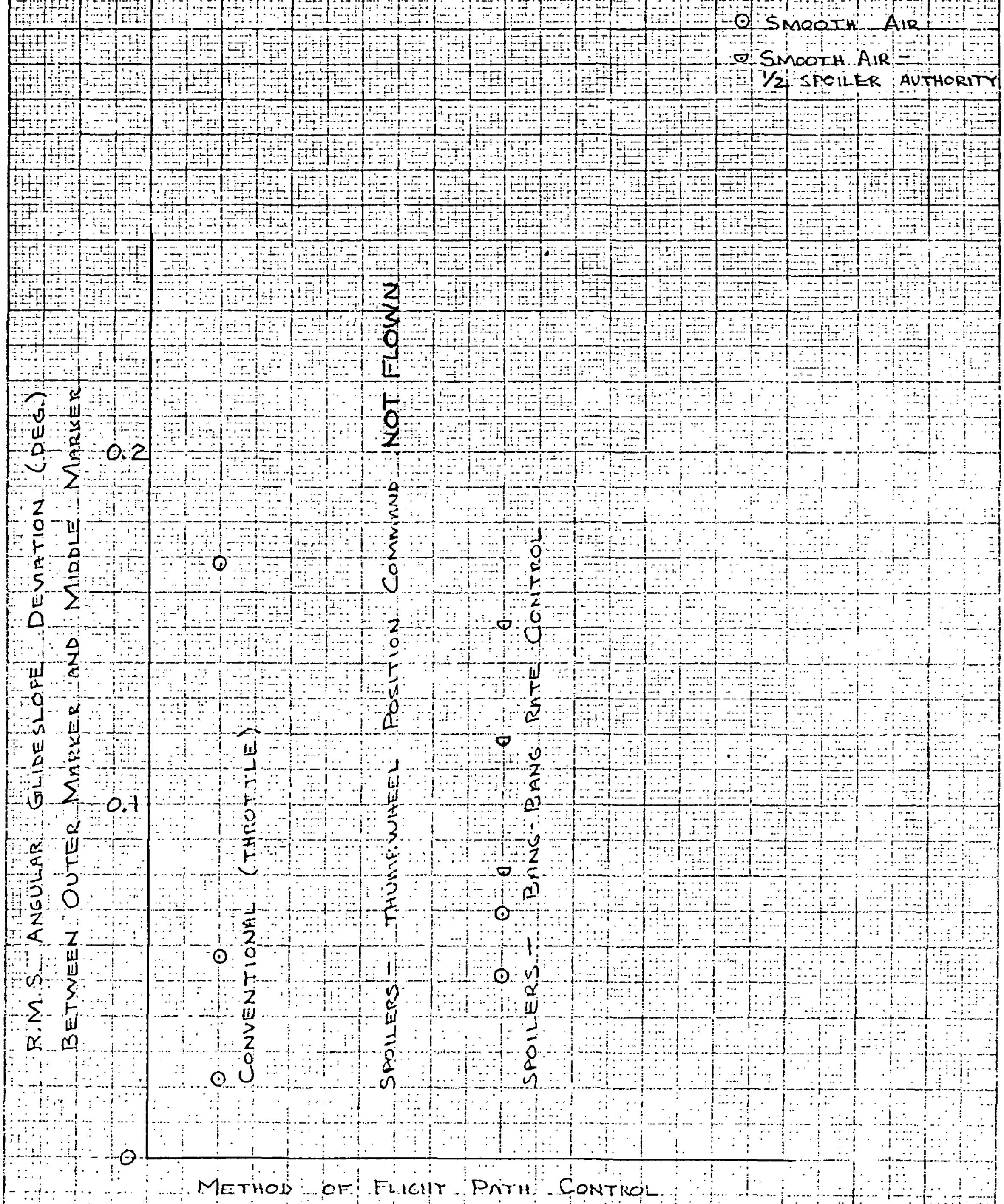
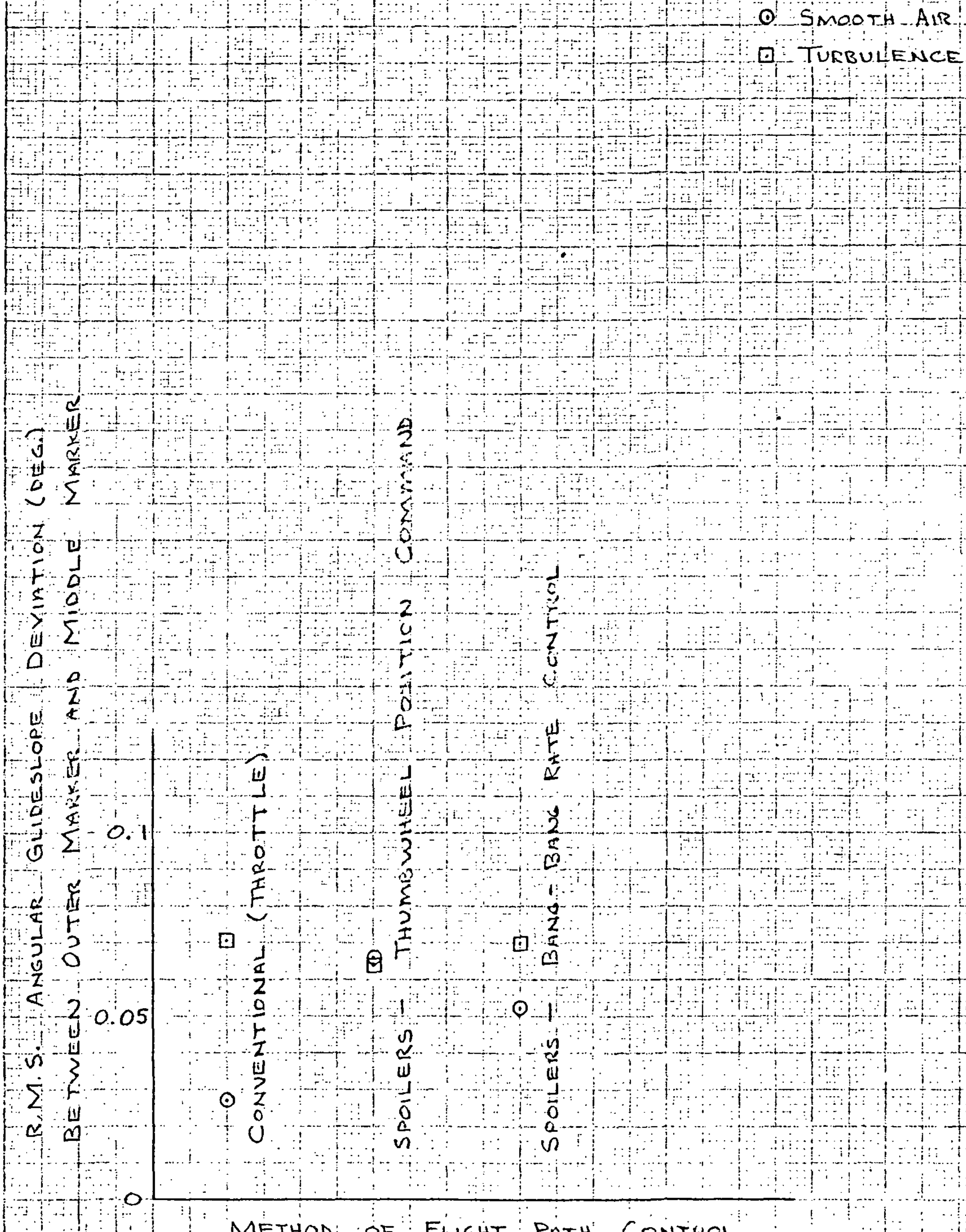


FIGURE 56

PILOT PERFORMANCE OF THE

ILS APPROACH TASK

PILOT G



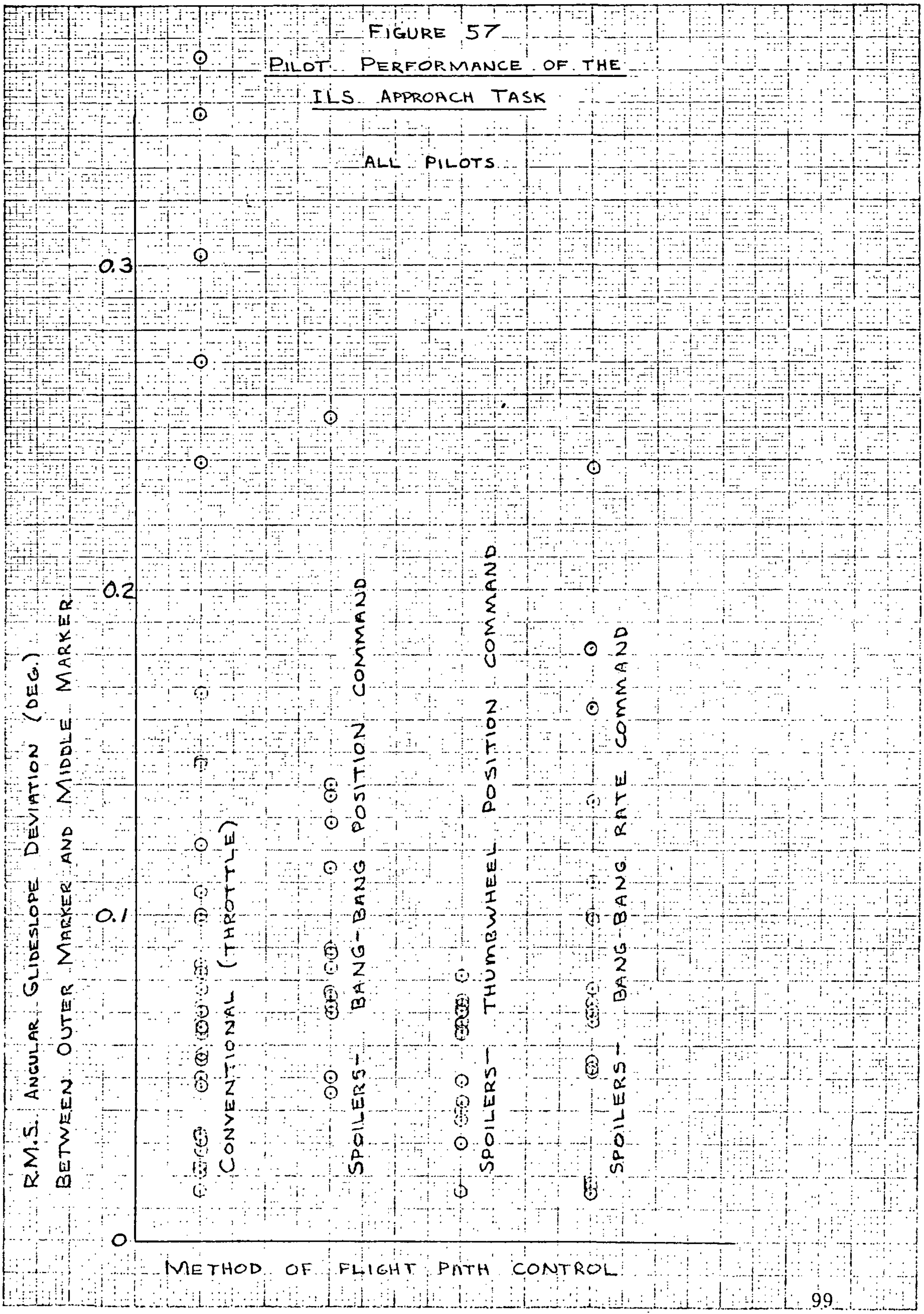


FIGURE 57
PILOT PERFORMANCE OF THE ILS APPROACH TASK

6. DISCUSSION AND CONCLUSIONS

At the beginning of this investigation, the spoiler system on the modified Cardinal was known as a "DLC" system. However, this work has demonstrated that a system giving direct control of aircraft lift coefficient, even if possible, is probably not a workable method of flight path control, at least on a light aircraft. Without some kind of automatic speed control the aircraft responds to a change in C_L by seeking a new trim speed; any change in flight path is only incidental. In a landing approach it is desirable to hold constant speed. On the other hand, a spoiler system rigged to hold aircraft C_L essentially constant has been shown to be a very effective and easy-to-use descent rate control, i.e., flight path angle control. With this system, the aircraft could be maneuvered at constant speed and attitude over a range of descent rates of about 320 feet per minute using only spoilers for control. These conclusions only apply to the modified Cardinal in landing configuration at 63 kt. At least for light airplane applications, the term "DLC" seems to be a misnomer. A better term might be "DRC" for "Descent Rate Control."

Spoiler pitching moment has a great bearing on the handling qualities of a spoiler control system. If $M_{\delta_{sp}}$ is zero or negative the spoiler system is similar to a pure DLC system, and the changes in trim speed and pitch angle caused by spoiler deflection result in an undesirable amount of phugoid activity. Control over flight path in a short time frame is not very precise. When the spoiler pitching moment is large in the positive direction (nose-up) the

above comments also apply. In addition, the initial aircraft response to a spoiler input is in the opposite direction to that intended, so handling is also unsatisfactory in this case. Spoilers which give just enough nose-up moment to keep aircraft C_L constant give the best handling qualities in the form of minimum phugoid excitation and effective control of descent rate. The spoilers actually control descent rate by changing aircraft drag, or lift-drag ratio.

The discussion above might lead one to the conclusion that a pure speedbrake would give good performance, since that would also be a constant C_L system. Recall from Section 4.1.2 that the drag of the spoilers was the principal contributor to airplane response. Comparison of Figures 20 (constant C_L spoilers) and 23 (speedbrake) shows that the effects of spoiler and speedbrake are nearly identical. The degree of phugoid excitation is identical, and neither system changes the aircraft trim speed. The speedbrake does affect pitch angle, while the spoilers do not. Both spoilers and speedbrake added the same drag increment to the aircraft. The descent rates were 160 fpm with the spoilers and 90 fpm with the speedbrake. The spoilers caused a higher descent rate because when they deflected they caused the aircraft to increase angle of attack. While this maintained total aircraft lift coefficient constant, it caused an increase in basic airplane drag which added to the spoiler drag. The relative merits of spoilers vs. speedbrakes as a descent rate control can be summarized as follows:

A. Spoilers

1. Advantages

Can maneuver at constant attitude

Effectiveness may be augmented by increased airplane drag due to angle of attack.

Spoilers can provide increased braking efficiency after landing by spoiling some wing lift.

2. Disadvantages

For good handling, spoilers may need elevator interconnect for proper pitching moment. Differing c.g. locations could make this difficult to rig properly.

Non-linear spoiler lift and drag may complicate pitching moment corrections. This simulation used linearized spoiler aerodynamic coefficients.

Increased angle of attack when spoilers are deflected reduces stall margin.

B. Speedbrake

1. Advantages

No elevator interconnect needed if properly designed

Does not affect wing or stall characteristics

Not affected by c.g. shift

2. Disadvantages

Pitch attitude not constant during maneuvering

Larger drag increment may be needed to match performance of spoilers.

Because spoiler pitching moment is potentially such a troublesome problem, light aircraft Descent Rate Control can probably be implemented easier in the general case using the speedbrake philosophy.

The ILS approaches flown by the evaluation pilots clearly showed the effectiveness of a good descent rate control system. All the pilots indicated that they liked the idea of not having to contend with the throttle on final approach. The throttle is somewhat difficult to use on an ILS approach because it is really more of a gross control

than a precise control. Evaluation pilots were observed tapping the throttle in an effort to get a small correction. This action would naturally tend to divert most of one's attention away from the flight instruments. In light aircraft the throttle can induce large trim changes (Reference 12). Throttle friction and the problem of propellor synchronization in multi-engine aircraft also tend to make the throttle unsuitable for a precision flying task such as the ILS approach. Therefore, it is not surprising that the pilots liked having very precise control of descent rate literally at their fingertips. They commented that the spoilers were generally easier to use than conventional methods. In addition, the approaches flown by most pilots were more consistent using the spoilers. The reduced pilot workload which is possible using spoilers to control precision instrument approaches surely has a potential for increasing safety. It is interesting to note that sailplanes have had good success using spoilers/speedbrakes as the primary flight path control in the landing approach.

The test results showed the advantage of a control system having continuously variable position. The bang-bang position type control could be used to keep the aircraft near the glideslope, but the frequent, large control inputs necessarily used made the system act like a built-in turbulence generator. The greater precision and smoothness of the thumbwheel and bang-bang rate controllers made them much superior. The choice of which one to install initially in the modified Cardinal is mostly a matter of practicality. The easiest installation would probably be the bang-bang rate controller, since it requires no position feedback control system.

A spoiler position indicator on the instrument panel is required with either spoiler controller. To make it distract as little as possible, the indicator should be positioned where it can be included in a normal scan of the primary flight instruments.

A possible controller not evaluated on the simulator is a separate throttle-like lever on the power pedestal connected directly (mechanically) to the spoilers. For satisfactory operation of such a system, the control and friction forces would have to be low so that small, precise inputs could be easily made. For ILS work, the control lever would have to stay at whatever position it was placed. Accomplishing this with low friction and control forces would not be easy, unless the lever instead controlled servo-actuated spoilers, which would not feed back aerodynamic forces.

The attractive feature of the servo-driven spoilers on the modified Cardinal is that control forces do not concern the pilot. Thus, controller action can be set up as desired. The bang-bang rate controller lends itself to several different installations because of its simplicity. In the simulator, the thumbswitch was mounted on the throttle handle because it was felt that pilots would prefer to keep one hand on the throttle as usual. It would be just as easy to install the switch in the control wheel just like a regular trim switch. In an aircraft with manual trim the switch could go in the left control horn. This would still allow the pilot to keep a hand on the throttle. If the aircraft already had electric pitch trim, the spoiler switch would have to go on the right side. Then the pilot could not keep a hand on the throttle. Whether or

not this would be acceptable probably merits further study.

Still other control schemes could be used. One of these is a throttle-spoiler interconnect. Such a system has been flight-tested on a Beech Musketeer by Aeronautical Research Associates of Princeton, Inc. (ARAP, Reference 13). Their relatively large spoilers are controlled by one half of a split throttle lever. As power is reduced toward idle, the spoilers begin deflecting, thus increasing the effectiveness of the throttle as a descent rate control. When the throttle reaches the idle stop, the spoiler half of the lever can be brought further back against a spring to give greater spoiler deflection. Thus, the combined throttle/spoiler control is like a throttle with increased effectiveness and extended authority.

Pilot A had an opportunity to fly the ARAP Musketeer during this investigation. He reports that the spoiler system makes visual approaches quite easy to fly with good accuracy. The combined throttle/spoiler control is a very powerful flight path control. While he considered the system to be a desirable innovation for visual approaches, he did not think it would be satisfactory for controlling ILS approaches because of its great sensitivity.

The ARAP system is used primarily to fly normal to very steep visual approaches with powerful descent rate control and without speed buildup, and to make positive touchdowns on command from the landing flare position. This capability is intended to cut down on overshoots and long landings. However, this system does not appear to be ideally suited for controlling ILS approaches in the manner demonstrated by this investigation. The capabilities of the Musketeer's spoilers

are so great that they are even more sensitive than a conventional throttle. Flying an ILS approach requires precise control of descent rate; changes of only 20 - 40 fpm may often be required. Flying visual and precision instrument approaches requires quite different capabilities in flight path control. One requires a powerful control, and the other requires a very precise control.

If the predicted aerodynamic coefficients of the modified Cardinal spoilers are in fact reasonably close, no elevator interconnect will be needed to achieve good handling qualities. The predicted spoiler pitching moment is within 10 % of that required for constant C_L with flaps down. The modified Cardinal is unusual in that its predicted c.g. envelope is much farther forward (3 - 9 %) than normal. So in this specific case spoiler pitching moment about the c.g. is not a strong function of c.g. position within that envelope. This might not be true for an aircraft with a c.g. range closer to the spoiler center of pressure.

A desirable feature of any spoiler system would be automatic retraction in the event of a missed approach to assure maximum climb performance. A cut-off switch on the throttle set to trip at a given power setting would do the job. Such a switch could disable the normal spoiler control and command the servo to retract the spoilers. A motor-cutoff microswitch activated when the spoilers reach the fully retracted position would complete the go-around safety system.

Two potential troubles with the spoiler lateral control system came to light during the evaluation flights. First, the predicted

spoiler rolling moment and wheel-spoiler gearing produced a system which the pilots generally felt was much too powerful and sensitive for easy control. Second, several pilots complained about the doubling of roll control power which took place when spoilers were biased up symmetrically. Flight tests should indicate quickly whether any real problems exist in these areas.

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